PALEOENVIRONMENTAL CHANGES AT TREELINE IN CENTRAL ALASKA: A 6,500 YEAR LONG POLLEN AND STABLE ISOTOPE RECORD

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A

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ABSTRACT

Combined pollen, macrofossil and stable-isotope records from two lakes in the sub-alpine zone of the north-central Alaska Range indicate significant changes in vegetation and lake productivity during the past ~6,750 ^{14}C yrs BP. These changes are associated with Neoglacial cooling and climate variations during the Little Ice-Age (LIA). Highest spruce densities occurred during a period from 5,000 ^{14}C yrs BP and 2,500 ^{14}C yrs BP and coincided with the onset of cooler and moister climate. The shifts in climate, which resulted in increased effective moisture levels in Central Alaska, possibly shifted the competitive balance towards spruce and against tundra taxa. Lake productivity declined as climate cooled. A brief episode of climate amelioration between 1,500 ^{14}C yrs BP and 800 ^{14}C yrs was followed by cooling events of the LIA which resulted in decreased spruce densities in the sub-alpine forest-tundra zone and a possible lowering in treeline at higher elevation.

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CHAPTER 1: INTRODUCTION

Objectives of study

Recent studies in global climate research predict rapid climate changes for the 21st century that will have major impacts on the environment. Global Circulation models project the most pronounced effects at high northern latitudes (Kutzbach and Ruddiman, 1993). Whether future climate change is triggered by anthropogenic activities or natural cycles, understanding how and why climate has varied in the past is the key for making accurate predictions about the implications of climate change in the future. Furthermore, studying the response of paleovegetation to past climate fluctuations provides useful insights regarding responses of the vegetation to future climate events.

Assessing changes of arctic and sub-arctic boreal treelines has recently become a major focus in climate research. The boreal forest at or near its altitudinal and latitudinal limits is considered extremely sensitive and a valuable source of paleoclimate and paleoecological information. Numerous studies have shown that circumpolar and alpine treelines have been very dynamic during Holocene times. While a large quantity of data has been gathered from Canada and northern Europe, little is known about the history of Alaskan treelines.

The following study investigated environmental changes in an alpine treeline ecotone with respect to climatic fluctuations during the Mid- to Late-Holocene. The main purpose of this research was twofold: gaining a better understanding of the nature and magnitude of Mid- to Late-Holocene climate fluctuations in Central Alaska using a multi-proxy approach, and obtaining new insights into the dynamic of the alpine treeline in Alaska, in particular the behavior of spruce trees in response to climatic changes during the past 6,000 years.

Research questions

1) Does the lake sedimentary record show any evidence of climate change during the Holocene, particularly shorter-term climate fluctuations such as the Neoglacial cooling, Medieval Warm Period, Little Ice-Age cooling and 20th century warming?

2) How did climate during the Mid- to Late-Holocene affect landscape and vegetation, specifically spruce, at treeline in Central Alaska?

3) How does the response of treeline vegetation, particularly the response of spruce, compare to other Holocene records from the Alaska Range and Central Alaska?

Paleoclimate records from glaciers and tree-rings

Glacial and tree-ring records from Alaska and adjacent arctic regions indicate that climate has changed significantly throughout the Holocene. Calkin and Wiles (1991) propose that glaciers in Alaska began to advance as early as 7,000 yrs BP and show a periodicity of 350 years after 4, 500 yrs BP in some areas. Glacial advances in higher mountains of central and northern Alaska indicate cooler climate between 4,500 yrs to 3,000 yrs BP. This was followed by an interval of slightly milder climate after approximately 2,000 or 1,000 yrs BP (Hamilton, 1986). Evidence from the north-central Alaska Range records several glacial advances during Holocene times. Radiocarbon dates, tephrochronology and lichenometry indicate that advances of the Gulkana Glacier occurred around 5,700 ± 260 yrs BP, 4,100 ± 800 yrs BP, 3,600 ± 700 yrs BP and during the Little Ice-Age (LIA) around 800 ± 125 yrs BP and 150-200 yrs ago (Beget, 1994). Although the LIA is recorded by advances of both land-terminating and fjord-calving glaciers in Alaska as early as the 13th century, glaciers did not reach their maxima until the 16th or even mid-18th century (Calkin and Wiles, 1991). Important Little Ice-Age expansions of several glaciers in the Alaska Range occurred around ~AD1390, ~AD1560 at the end of the 19th century (Calkin and Wiles, 1991). A recent rise in firn limit and the retreat of Gulkana Glacier suggests a warming trend since the LIA maximum.

Tree-ring data sets from high-latitude regions provide further evidence of climate cooling during the Little Ice-Age and subsequent warming during the past century. Climate reconstructions from arctic environments, e.g. in Alaska, Canada, Russia and Scandinavia, suggest that annual temperatures were much lower during a period from approximately AD1680 to AD1720 and AD1800 to AD1910 (D'Arrigo and Jacoby, 1993). Intervals of cool temperatures are interrupted by a warming trend during the mid to late

18th century (D'Arrigo and Jacoby, 1993). A trend towards elevated annual temperatures is also observed since the early 20th century. An analogous data set from treeline sites in northern and central Alaska indicates similar results. Ring-width based annual temperature reconstructions show that cooler temperature prevailed before AD1900 (Jacoby and D'Arrigo, 1995). The period of cool climate was interrupted by episodes of warmer intervals, specifically during the 18th century, which suggests that the Little Ice-Age can be considered a generally cooler period, but that relatively normal climate was experienced spatially and temporally during this interval (Jacoby and D'Arrigo, 1995). The trends seen in Alaska are also observed from treeline sites in Northwestern and Central Canada, where tree-ring evidence indicates increased growth during the mid- to late 18th century and decreased growth during the early to mid 19th century (Szeicz and MacDonald, 1995; MacDonald and Szeicz, 1998).

While Late-Holocene climate changes are well documented in the tree-ring and glacial record, little is known about how these cooling events are documented by other proxies, such as pollen records. This is due to the fact that high-resolution Holocene data are essentially missing from Alaska.

Treeline response to climate fluctuations

Treeline is defined as the ecotone between forest and tundra biomes where trees are growing at their physiological limits. Treelines are dynamic systems in which environmental conditions control the dynamics of tree populations through balancing recruitment and mortality (Brubaker, 1986; Hustich, 1983). The common tree at latitudinal and altitudinal treelines in Alaska is *Picea glauca* (Moench) Voss (white spruce). The position of treeline is strongly dependent on mean summer temperatures and roughly coincides with the 10°C summer isotherm, which is true for altitudinal and latitudinal treeline (Grace, 1989; Hustich, 1983). Tree-ring studies of *Picea glauca* at treeline sites in Alaska and Canada show that tree growth is strongly related to summer surface air temperatures. However, it has a higher correlation to annual temperatures averaged over the previous 3 to 5 years (Jacoby and D'Arrigo, 1995). Apart from temperature, additional, often local, environmental factors such fire, wind, frost damage and soil development may dictate and alter stand dynamics in the treeline ecotone

(Grace, 1989; Payette and Gagnon, 1985). In northern Quebec, *Picea mariana* (black spruce) and *Larix laricina* (tamarack) have been unable to regenerate after fire during the past 3,000 yrs BP, which has resulted in deforestation and the formation of a treeless biome (Payette and Gagnon, 1985; Gajewski et al., 1993).

The response of treeline vegetation may be complex and depends on the position of the ecotone in space and time and its "susceptibility" to disturbance (Scott et al., 1987; Hofgaard, 1997). Studies have shown that treeline may remain in a state of non-equilibrium, or inertia, in which the position of treeline remains unaltered by ongoing climate changes because it is still responding to a previous climatic event (Scott et al., 1987; Payette et al., 1989). A displacement of the actual treeline may not occur, even when treeline vegetation is responding positively to climate warming by increased stand density (MacDonald et al., 1998). A state of dynamic equilibrium is reached if the trees at treeline can extend beyond their limits as determined by the existing climate parameters (Payette, et al., 1989, Brubaker, 1986). Regeneration beyond treeline occurs by new seedling establishment or by phenotypic adaptation of some species, e.g. the ability of trees to change from a layered to an upright growth form (Payette and Gagnon, 1985; Kullman, 2000).

Changes in the location of treeline and the dynamics within the treeline ecotone vary widely on a temporal and spatial scale. In Alaska and western Canada, the retreat of the Pleistocene ice-sheet was followed by a large-scale dispersal of *Picea glauca* from glacial refugia (Ritchie and MacDonald, 1986). Treeline displacement can take place extremely rapidly and may be limited to a smaller region. For example, northward movement of treeline around 5,000 years BP in North-Central Canada and the subsequent transformation of tundra to forest-tundra occurred within 150 years according to diatom and pollen records (MacDonald et al., 1993).

There have been significant changes of treelines in some arctic and subarctic regions during Holocene times. Studies from Western and Central Canada show a long-term trend towards declining latitudinal treeline since the Mid-Holocene (Spear, 1983; Moser and MacDonald, 1990; Cwynar and Spear, 1991; Gajewski and Garralla, 1992). Treeline retreat as a function of climate cooling is also observed in Siberia (Wolfe et al., 1999). In Labrador, climate change during the past 3000 yrs BP had a significant impact on the elevation of altitudinal treeline but no detected effect on the latitudinal limit of

trees (Lamb, 1985). Additionally, recent treeline changes have been well documented from Northern Quebec and Sweden (Kullman, 1983; Payette, 1983; Payette et al., 1985; Kullman, 1988; Payette et al., 1989; Kullman, 2000). The history of altitudinal treeline in Central Sweden is controlled by autecological difference among the tree species present in the ecotone (Kullman, 1983). The main tree species in this region are *Pinus sylvestris* (Scots pine), *Betula pubescens* (downy birch) and *Picea abies* (Norway spruce). The elevation of pine treeline has declined since the Early Holocene. A subalpine belt of *B. pubescens* and *Alnus incana* woodlands developed below the pine forest in the Mid-Holocene when climate was at a thermal optimum (Kullman, 1983, Kullman, 1988). The birch/alder belt gained in altitude until 3,000 yrs BP when climate deterioration resulted in a major treeline decline. A decline in birch and pine is also noted during the LIA. However, tree limits of all species appear to have risen during 20th century warming (Kullman, 1988; Kullman 2000).

Although the post-glacial history of spruce is well documented, little is known about the effects of climate changes on spruce growth in the treeline ecotones of mountain regions in Central Alaska during the latter part of the Holocene. Previous studies from Central Alaska suggest that that spruce at alpine treeline did not respond to LIA cooling (Ager, 1983; Anderson and Brubaker 1994). However, there is evidence that spruce has responded positively to 20th century warming. In the Noatak Valley in northwestern Alaska, climate amelioration during the past century resulted in changes in population dynamics and minor upslope movement of *Picea glauca*. At the same time, no major advance of the latitudinal treeline was observed (Rowland, 1997). Tree establishment of *P. glauca* has been constant in this area for the past 400 years and continued even when climate deteriorated during the LIA.

Previous studies from mountain regions in Central Alaska

Several paleoecological records have previously been published from the Alaska Range, all of which investigated the vegetation history at or above present altitudinal treeline using pollen analysis. Two records (Ager and Sims, 1981; Schweger, 1981) have been published from Tangle Lakes, which are located in the upper Delta River Region along the eastern portion of the Denali Highway (Fig. 1). The lakes today are

surrounded by shrub tundra with a few scattered spruce in the area. A 2,600-year record of pollen and macrofossils from high-level shore sediments of Long Tangle Lake suggests that *Picea* entered the region around 9,100 yrs BP (Schweger, 1981). A lake sedimentary record from Long Tangle Lake spanning the past 4,700 yrs BP suggests that *Picea* was sparse before 3,500 yrs BP but increased in density after that (Ager and Sims, 1981). There is a 4,300-year gap between Schweger's postglacial and Ager and Sims' Late-Holocene record. Ager and Sims hypothesize that *Picea* disappeared from the region after 9,000 yrs BP, similar to the decline of the spruce population at some sites in Interior Alaska between 8,400 yrs BP and 6,400 yrs BP (Ager and Sims, 1981; Hu et al., 1993).

Pollen percentages from nearby Ten Mile Lake (Fig. 1) suggest that *Picea* arrived on the landscape around 9,100 yrs BP, which agrees with Schweger's observations (Anderson et al., 1994). *Picea* percentages do not vary significantly throughout most of the Holocene, however, and exhibit high values (ca. 20-30%) that are normally characteristic for forested areas (Anderson et al., 1994). Ten Mile Lake is located above modern treeline with trees growing about 5 km to the east. The high percentage values reflect wind dispersal from spruce populations growing at lower elevations (Anderson et al., 1994). *Picea* influx rates at Ten Mile Lake show low values between 8,000 and 7,000 yrs BP, indicating a possible drop in nearby treeline elevation (Anderson et al., 1994). However, the overall *Picea* population density did not change during the early Holocene at lower elevation in this region. There is little evidence that *Picea* population declined at higher elevation or for any vegetation change at Ten Mile Lake during the Mid- to Late Holocene. The increase of *Picea* percentages around 3500 years BP at Tangle Lakes is not observed at Ten Mile Lake.

The previously published records from Tangle and Ten Mile Lakes differ significantly. The Mid- to Late-Holocene history of spruce in the north-central Alaska Range remains unclear, and has not been examined in a high-resolution record. This study attempts to shed light into the latter part of the Holocene record.

Regional settings

Geology and topography. The location of this study is Central Alaska, more specifically the north-central part of the Alaska Range. The Alaska Range forms a mountain belt extending approximately ~1,200 km from the Aleutian Range in southwest Alaska to the Canadian border (Fitzgerald et al., 1995). The mountain range is defined by the Denali fault system, a right-lateral strike-slip fault that formed during the Mesozoic along the line of a continental suture (Fitzgerald et al., 1995). The central portion of the Alaska Range consists largely of a number of terranes that were accreted onto the North American continent by a northward motions during the late Mesozoic (Trop and Ridgway, 1997). Today's topography of the Alaska Range varies from region to region. Gently rolling hills, which are common at lower elevations, are interspersed with high mountain peaks. The tallest peaks are located in the western part of the Alaska Range, with Mt. McKinley being the highest mountain at an elevation of 6,195 m.

Vegetation. The present-day vegetation in Central Alaska and the Alaska Range depends on several factors, including topography, elevation, aspect and the presence of permafrost. Lower lying areas and valleys of the Alaska Range are characterized by boreal (or taiga) forest, which comprises stands of *P. glauca* (white spruce) and *P. mariana* (black spruce), while higher elevations in the forest-tundra and alpine tundra zones are characterized by open white spruce forest, mesic shrub woodlands and mixed herb-heath tundra (Viereck, 1992). Local taxa at the study sites includes shrub species such as *Betula glandulosa* (dwarf birch), *Alnus* spp. (alder), *Salix* spp. (willow), ± *Ribes hudsonianum* (northern black currant), various *Cyperaceae* (sedges) and *Poaceae* (grasses), common shrubs and herbs such as *Cornus canadensies* (dwarf dogwood), *Potentilla fruticosa* (tundra rose), *Sanguisorba stipulata* (Alaska burnet), *Anemone parviflora* (Alpine anemone), *Arnica frigid*a (snow leopardbane), *Aconitum delphinifolium* (monkshood), as well as heath types (Ericaceae) such as *Vaccinum uliginosum* (bog blueberry), *Vaccinum vitis-idea* (low-bush cranberry), *Ledum palustre* (labrador tea), *Arctostyphalos rubra* (bearberry) and *Cassiope tetragona* (mountain heather). Common moss types include *Sphagnum* sp. (peat moss) and *Lycopodium annotinum* (club moss).

Climate. The Alaska Range is generally characterized by low annual temperatures and relatively low annual precipitation, most of which is released in the form of rain during the summer months. Climate records are available from weather stations in the north-central and western Alaska Range. The data reported below is from Cantwell, which is closest to the study sites discussed here. The mean annual temperature at Cantwell is –3.2°C, with mean winter temperatures (December through February) of -16°C and mean summer temperatures (June through August) of 11.2°C. Mean annual precipitation is 428.8 mm, with mean winter precipitation of 75 mm and mean summer precipitation 197.4 mm. This summary is based on climatological data observed during the past 18 years by the National Weather Service.

Glacial and vegetation history. While a large area of Central Alaska to the north of the Alaska Range was unglaciated due to lack of moisture, the Alaska Range itself experienced several glacial episodes during the Late-Pleistocene (Ten Brink and Waythomas, 1985; Hamilton, 1994). Glacial geomorphologic features cover most of the upland of the Alaska Range and are representative of the Donnelly (northeastern/ northcentral Alaska Range) and Farewell complexes (western Alaska Range), respectively (Hamilton, 1994). Most glaciers had retreated between 12,000 to 10,000 yrs BP (Ager, 1981; Schweger, 1981). During late Wisconsin time, the unglaciated part of Central Alaska was sparsely vegetated and low in productivity. Sites from Central Alaska suggest that *Artemisia*, *Cyperaceae* and *Poaceae* dominated the landscape (Ager, 1993). A significant change occurred between 14,000 and 12,000 yrs BP when *Betula*, in the form of dwarf birch, entered the region (Ager, 1983; Anderson and Brubaker, 1993). Between 10,000 yrs BP and 8,500 yrs BP, *Populus* became more abundant and had entered the valleys of the Alaska Range (Ager, 1983), but it declined rapidly afterwards (Bigelow, 1997). *Picea glauca* became abundant at about 9,000 yrs BP. Trees were present in the Delta River Region of the north-central Alaska Range as early as 9,100 years BP and spread quickly east- and northward (Ager and Sims, 1981; Ager, 1983). *P. glauca* arrived in the western Alaska Range between 8,000 yrs BP and 7,500 yrs BP (Ager, 1983; Hu et al., 1996). Along with *P. glauca*, *Alnus* entered the landscape between 8,000 and 7,000 yrs BP. The modern boreal forest of Central Alaska was established between 6,000 yrs BP and 4,000 yrs BP when *P. mariana* became more

important and subsequently replaced *P. glauca* as the dominant tree species (Anderson and Brubaker, 1993).

Methods

Field sampling. Sediment cores from Swampbuggy and Nutella Lakes were collected in September 1996 using a modified Livingston piston corer (Wright, 1987). The cores were extruded upon retrieval into PVC core holders, and sealed for transport. Surface cores were collected using a clear tube in order to obtain an undisturbed sediment-water interface. The top 10-20 cm of all surface cores were extruded at 1 cm increments and stored in whirlpacks. The remainder of the surface cores were sealed and transported in an upright position to the laboratory. Upon return to the laboratory, magnetic susceptibility was measured on all cores using a Bartington Susceptibility Meter. The cores were then split in half, cleaned and refrigerated at 4ºC until further analysis. Before any sub-sampling was conducted, the sediment lithology was noted and the cores were photographed for further reference.

Loss-on-Ignition (LOI) analysis. Loss-on-ignition determines the approximate content of organic and inorganic carbon in the sediment. In a first step, 1cm^3 samples were placed in a heat-resistant crucible and dried for at least 20 hours at 80°C. The samples were weighed prior to and after drying in order to determine the water content as well as wet and dry densities of the sediment. The samples were subsequently placed into a muffle furnace, baked for 2 hours at 500°C and re-weighed. The weight loss, calculated as a percentage of the dry weight, provided an estimate of the organic matter content of the sediment. The samples were once again placed into the furnace and baked for another 2 hours at 850°C to assess the inorganic carbon content of the sediments.

Isotope analysis. Stable carbon and nitrogen isotopes were measured on undifferentiated lacustrine organic matter using an EUROPA elemental analyzer mass spectrometer. One cm thick slices of sediment were prepared for each sample. The samples were soaked overnight in 5 ml weak hydrochloric acid solution (1N) in order to

remove inorganic carbon. The samples were then rinsed twice with ultrapure de-ionized water and freeze-dried. The amount of dried sample that was analyzed in the mass spectrometer depended on the nitrogen content of the sediment and varied between 2 to 80 mg. The nitrogen content was estimated from the organic matter content obtained through LOI analysis.

Pollen preparation and analysis. The processing of pollen samples followed standard procedures outlined by Faegri and Iversen (1989). 1 cm^3 sediment samples were collected at 2.5 cm intervals and dissolved in weak 10% HCL solution to which a known quantity of *Lycopodium clavatum* spores were added. The sample was then sieved through a 250 μm mesh screen and soaked in hot potassium hydroxide solution for 10-15 minutes in order to remove humic acids. In a next step, the sediment was washed with dilute hydrochloric acid for carbonate removal followed by a boiling water bath of concentrated hydrofluoric acid to dissolve silt. Acetolysis followed for 1 minute. The samples were stained with safranin, dehydrated with TBA (tert-butyl-alcohol) and mounted in silicon oil. Pollen slides were counted at 400x under a Nikon Optiphot light microscope until a minimum of 300 pollen grains of the basic pollen sum (trees, shrubs and herbs) was reached.

Macrofossils. Macrofossil analysis was conducted on the archive halves of the cores. The cores were sliced into 2 cm thick sections. The volume of each section was determined by water displacement. The sediment was sieved through a 125 μm screen and the portion caught in the screen transferred to sandwich bags for further detailed analysis. Prior to sieving, clumpy or otherwise silty samples were soaked in 5% sodium pyrophosphate overnight before sieving in order to break up coarser particles. Macrofossils were identified using a dissecting microscope at 10x or 50x. Identified macrofossils were cleaned and stored in distilled water. Spruce needles and larger plant fragments were used for AMS radiocarbon dating.

Spruce stomates. Stomates are openings on a plant leaf for CO_2 conduction and water regulation. Stomates are made of very resistant cellulose-like material and are well preserved in the lake sediment. Extraction from the sediment follows the basic

procedures of pollen preparation. The occurrence of spruce stomates was noted during pollen counting. In most instances, however, it was necessary to scan several additional slides at a single level in order to encounter a significant number of stomates. For Swampbuggy Lake, stomates were counted until a pollen sum equivalent (PSE) of at least 2,000 and 3,000 at crucial levels was reached. The PSE is calculated by extrapolating the number of exotic pollen grains that have been tallied in the pollen count against the number of exotic grains that are tallied during stomate counting. Stomates types were identified using the description by Hansen (1995) and by comparison to reference slides of modern stomates.

References slides were made using needles from modern spruce trees (both black and white spruce) that were collected in the Fairbanks area. In order to extract the stomates, the collected needles were finely sliced with a razor blade. They were processed using basic pollen preparation procedures (except HF wash). Modern stomates were also examined under the Scanning Electron Microscope (SEM) in order to observe more subtle differences between black and white spruce stomates. No significant size differences between Alaskan white spruce and black spruce stomates were observed under the light microscope, although other morphological characters were in good agreement with the descriptions by Hansen (1995).

Radiocarbon dates. AMS radiocarbon dates were obtained from plant macrofossils, mostly spruce needles, and spruce pollen at levels where macrofossils were not available. Pollen was extracted by heavy liquid separation using the methods by Brown et al. (1989).

CHAPTER 2: SWAMPBUGGY LAKE

Introduction

Swampbuggy Lake (official name, N63°41', W147°40') is located in the upper catchment of the Susitna River at an elevation of 813 m at lake level (Fig. 1) The lake basin may have filled as a result of glacial melting processes, although the actual age and origin of the lake is unknown. Swampbuggy Lake has a moderate size (14 ha), is relatively shallow (max. water depth 4.2 m) and has a gently sloping, almost flat, single basin. No inlets or outlets have been observed. Secci depth measurements in summer 1996 averaged to about 3.55 m. Water chemistry analysis indicated that the lake was not stratified and showed no signs of anoxia during the summer months. Water surface temperature in July 1996 was 19.6 °C. The lake water is alkaline and has an average pH value of 8.13. Macrophyte growth is restricted to the western and southern margins of the lake, which are less rocky. Swampbuggy Lake is currently surrounded by mesic shrub tundra of mostly alder and some birch to the N and NW, and dense forest-tundra to the S and SE (Fig. 2). The treeline and species limit of spruce is located at roughly 850 m. The north side of the lake is confined by a very steep mountainside, which limits the local extent of trees.

Two cores, each of approximately 171 cm length, were retrieved from Swampbuggy Lake (SBL): SBL A and SBL B. Both cores were taken side by side at a water depth of 379 cm. The following results derive from SBL Core B mainly, unless otherwise indicated. Originally, 186 cm of sediment were retrieved but the bottom 15 cm (186 cm to 171 cm) were omitted as they were not stratigraphically in place due to the coring process. Core depth is reported relative to the lake water surface.

Results

Sedimentology. Swampbuggy Lake sediments mainly consist of brown to dark brown organic sediments (Fig. 3). Intermittent layers of grayish silt-rich material appear at various levels but are most frequent in the lower half of the core (550 to 490 cm). These

silt layers probably represent events where silt was washed out from the shore bank or hill sides into the lake. 1-2 cm thick bands of lighter and darker brown organic sediments are characteristic for the lower half of the core until approximately 490 cm. The bands are faint, and may represent distinct periods of high and low organic content. The upper half of the core from 490 cm to 379 cm consists of homogenous dark brown organic sediments and does not show any bands. A prominent tephra layer, the Jarvis Ash (Beget, 1994), is located halfway through the core between 479 cm to 485 cm and serves as an age control and a stratigraphic marker. The Jarvis Ash originated from an eruption of Mt. Hayes on the Alaska Peninsula and it is found at various sites throughout the Alaska Range region. Despite its distance to the source (~650 km), thicknesses of up to 7 cm have been reported locally (Beget et al., 1991). Several other tephra layers (<3 mm thickness) are found in the core at 494 cm and 499 cm but have not been identified or dated. The lower transition of Jarvis Ash is very abrupt while the top of Jarvis gradually blends together with the organic fraction of the sediment. The interval just above Jarvis from 475 cm to 465 cm is extremely macrofossil-rich and includes several spruce needles as well as traces of aquatic moss and charcoal. In addition, this sediment section just above Jarvis Ash contains a large amount of diatoms.

Age chronology. Eleven Accelerator Mass Spectrometer (AMS) radiocarbon dates were obtained from SBL CoreB (Table 1). All dates obtained are presented as uncalibrated radiocarbon ages, unless otherwise indicated. The age at the base of the core at 550 cm can be extrapolated to approximately 6,744 ^{14}C yrs BP.

Spruce needles were used for dating where abundant. At levels where macrofossils were lacking, pollen was dated instead. Dates from the upper part of the core (379 cm to 400 cm) were obtained using ^{210}Pb activities. The age-depth curve shows a good polynomial fit with an R^2 value of 0.9968 (Fig. 4). Two of the eleven processed radiocarbon dates were removed from the age-depth chronology as the data did not fit the trend of the other dates obtained. At 533-536 cm, two macrofossil dates have similar ages while the third date, a pollen sample, shows a much older age. The pollen date was omitted from further analysis as its exclusion from the age-depth model presented a better curve fit. At 455-457 cm, a macrofossil produced a much younger age than expected. This date was also omitted from the age model because the sample

was extremely small and produced a large error. The age-depth curve shows a good polynomial fit with an R^2 value of 0.99 (Fig. 4).

Table 1: ^{210}Pb and radiocarbon dates from Swampbuggy Lake.

	Depth	Age [yrs BP]	+/-	Material	Lab	Lab#
top	*379*	**0**	**0**	top		
^{210}Pb	*390*	**190**	**5**	undifferentiated sediment		
^{14}C AMS	*400-403*	**780**	**40**	pollen	L. Livermore Nat.Lab.	65459
^{14}C AMS	*414-418*	**1350**	**50**	pollen	L. Livermore Nat.Lab.	56433
^{14}C AMS	*430-433*	**1720**	**40**	pollen	L. Livermore Nat.Lab.	65460
^{14}C AMS	*455-457*	**1920**	**710**	macro 0.8687	L. Livermore Nat.Lab.	56434
^{14}C AMS	*455-457*	**2650**	**40**	pollen	L. Livermore Nat.Lab.	65461
^{14}C AMS	*477-479*	**3370**	**45**	spruce needle 0.63mg	INSTAAR/NOS AMS	NSRL-10371
^{14}C AMS	*479-485*	**3650**	**150**	*Jarvis Ash*	(see Beget, 1994)	
^{14}C AMS	*493-495*	**3860**	**50**	spruce needle 0.76mg	INSTAAR/NOS AMS	NSRL-10372
^{14}C AMS	*509-511*	**4860**	**40**	pollen	L. Livermore Nat.Lab.	65462
^{14}C AMS	*533-536*	**5980**	**50**	twigs 0.84mg	INSTAAR/NOS AMS	NSRL-10373
^{14}C AMS	*533-536*	**6530**	**40**	pollen	L. Livermore Nat.Lab.	65463
^{14}C AMS	*533-536*	**5660**	**140**	macro 0.05mg	L. Livermore Nat.Lab.	65464

Dates in shaded areas were omitted from the age model as discussed in the text.

Magnetic susceptibility and loss-on-ignition. Both magnetic susceptibility measurements and loss-on-ignition (LOI) analysis indicate changes in lithology and sediment content. The percentage weight loss at 500°C and at 850°C reflect the amount of organic and inorganic carbon, respectively. Magnetic susceptibility measures the

amount of magnetic material, and thus provides an additional measure for the concentration of inorganic terrestrial material. The relationship between magnetic susceptibility and LOI is inversely proportional (Fig. 5). Lower organic carbon values are found at levels of higher magnetic susceptibility where layers of tephra or silt are present in the core. Generally, organic carbon comprises 20% to 30% of the core. The weight loss percentages at both 500°C and 850°C do not show any significant long-term trend, however (Fig. 5). Weight loss percentages at 850°C are relatively low and show no considerable changes, which indicates that carbonates are absent in the core.

Stable isotope analysis. The carbon to nitrogen ratio (C/N) in SBL Core B is relatively low (Fig. 6a), with the majority of C/N values ranging between 9.5 and 12. Therefore, most of the organic matter is probably produced in the overlying water column. $\delta^{13}C$ and C/N are uncorrelated (Fig. 6a), e.g. $\delta^{13}C$ ratios change as much as 4‰ over relatively constant C/N ratios. The $\delta^{13}C$ values fall within the wide range found in aquatic organic matter (C/N < 12) (Meyers and Ishiwatari, 1993). The carbon isotopic signature is also positively related to the carbon content of the sediment organic matter, e.g. changes in %C follow the overall trend of $\delta^{13}C$ ratios (Fig. 6b). Thus, the carbon signal in the sediment appears to be controlled by processes in the overlying water column and reflects the isotopic signature of plankton in the surface waters.

The isotope data from Swampbuggy Lake can be divided into several distinct intervals (Fig. 7). $\delta^{13}C$ values are relatively high (around –22 ‰) from 550 cm to 515 cm (~6,750 to 5,000 ^{14}C yrs BP). Intervals of extremely low values correspond to silt-rich layers in the core and reflect occasional high input of depleted terrestrial carbon to the lake during these events. Elevated $\delta^{13}C$ ratios may be due to increased productivity in the surface water (Stuiver, 1975). Atmospheric CO_2 ($CO_{2(air)}$) may have been a contributing source of carbon to the lake adding ^{13}C-enriched material to the lake. Increased macrophyte production may been an additional factor contributing to increased $\delta^{13}C$ although no macrophytes macrofossils have been found in the sediment.

$\delta^{13}C$ values gradually decline to lower values between 515 cm to 485 cm (5,000 and 3,800 ^{14}C yrs BP). This decline is accompanied by decreased abundance of carbon in the sediment and slightly lowered C/N ratios (Fig. 7). Increased diatom content in the

sediment core shortly after the deposition of Jarvis Ash around 3600 ^{14}C yrs BP suggests that the lake may have been highly productive for diatoms (Fig. 3). Conditions for diatoms may have improved as these organisms were able to sequester larger amounts of dissolved silica added by the ash fall. However, lowered $\delta^{13}C$ values (-24‰ to –26‰) from 485 cm to 440 cm (3,800 to 2,000 ^{14}C yrs BP) as well as low %C values indicate an overall reduced lake productivity during this interval. Reduced productivity may have decreased the flux of enriched $CO_{2(air)}$ to the lake's DIC while heavily ^{13}C-depleted carbon, e.g. CO_2 from soil composition, may have been a more important carbon source.

The carbon isotope signal reverts to slightly increased values during a period from 440 cm to 405 cm (2,000 to 800 ^{14}C yrs BP). $\delta^{13}C$ ratios increase to values ranging from approximately –22‰ to –25‰ while carbon percentages slightly increase to about 12% (Fig. 7). C/N ratios remain relatively unchanged suggesting that larger amounts of terrestrial influx of ^{13}C-enriched carbon, for example through increased macrophyte growth, did not contribute to the change in $\delta^{13}C$. Thus, the increase in $\delta^{13}C$ is most likely due to increased productivity and a reduction in the depleted carbon source.

Carbon stable isotope ratios drop to values between –25‰ to –26‰ during a period from 405 cm to 390 cm (800 to 200 ^{14}C yrs BP). Carbon content in the sediment during this interval is slightly lowered ranging from 6-11% (Fig. 7). The carbon isotopic signal suggests that the interval from 405 cm to 390 cm is characterized by lowered lake productivity. ^{13}C-depleted DIC may have been a major carbon source to the lake's phytoplankton. A gradual increase in $\delta^{13}C$ ratios occurred from 390 cm to 379 cm (past 200 ^{14}C yrs BP) although the sediments in the uppermost few samples are slightly depleted. The carbon content in the sediment is increasing during this period indicating that the uppermost interval between 390 cm and 379 cm reflects a period of increased lake productivity.

No significant long-term changes can be observed from the nitrogen stable isotope record (Fig. 8). Variations in $\delta^{15}N$ ratios are relatively small and vary between 0.5‰ and 2‰ over nearly constant C/N ratios (Fig 9a). There is no significant correlation between $\delta^{15}N$ and the nitrogen content in the sediment (Fig. 9b) which indicates that variations in $\delta^{15}N$ are generated by complex nitrogen cycling processes and are not a simple function of aquatic organic matter input. There is a slight trend toward increasing

values from the core base, e.g. 550 cm, to approximately 390 cm (6,750 ^{14}C yrs BP to 200 ^{14}C yrs). The nitrogen content ranges between 0.5% and 1% below 470 cm (3,000 ^{14}C yrs BP) but shows a trend of slightly increasing values during an interval from 470 cm to 390 cm (3,000 ^{14}C yrs BP to 200 ^{14}C yrs BP) (Fig. 8). Factors affecting the observed changes in the nitrogen isotopic signal, such as productivity changes or changes in nitrogen cycling in the lake, are not easily identified as the variations of δ^{15}N are minor.

Pollen and macrofossil record. Pollen percentages from Swampbuggy Lake indicate that trees and shrubs dominate the pollen assemblage throughout out the core (Fig. 10). *Betula* percentages are slighter higher in the bottom of the core while the relative abundance of *Alnus* increases towards the top. An increase in *Picea* pollen can be observed between 520 cm and 485 cm (5,000 ^{14}C yrs BP to 3,500 ^{14}C yrs BP). Highest percentages are observed between 480 cm (3,500 ^{14}C yrs BP) and 450 cm (2,500 ^{14}C yrs BP), after which they gradually decline. Pollen percentages reach over 20%, which normally indicates the presence of forest (Anderson et al., 1994) A significant change of *Isoetes* spores occurs around 445 cm (2,200 ^{14}C yrs BP) when percentages rise from <10% to values over 20% and remain high in the upper part of the core.

Pollen percentages can be misleading as they only reflect the relative abundance of taxa. This is crucial at treeline because the presence of prolific pollen producers such as *Alnus* or *Betula* may overpower the presence of other important species. Upslope wind dispersal may then distort the actual signal at the treeline site (Anderson et al., 1994). Thus, pollen accumulation rates (PAR), representing the actual influx [grains/cm^2*yr] into the sediment over time, have been calculated and will be utilized in interpreting the landscape history. Combined with a macrofossil record (needles and stomates), a more accurate picture of the vegetation can be obtained. Unlike pollen, stomates and needles are not likely to be transported far from their site of origin (Clayden et al., 1996). Therefore, the macrofossil record reflects changes in the local taxa.

Pollen influx rates at Swampbuggy Lake have been grouped into three main zones and two sub-zones in order to better recognize the variability in the data (Fig. 11a-d). These zones were generated by statistical analysis (CONISS program developed by

E. Grimm) and visual inspection of the pollen diagrams. Figures 11a), 11b) and 11d) indicate a trend towards decreasing total accumulation rates above 485 cm. This change in influx rates is reflected across all terrestrial vegetation groups. Aquatic pollen and spores, in contrast, show a reversed trend with increased values near the core top.

Pollen zone SBL III (~6,750 to 5,000 ^{14}C yrs BP / 550 cm to 515 cm): This zone is characterized by relatively high influxes of shrub taxa, particularly *Betula* and *Alnus* (~1500 grains/cm^2*yr). *Juniperus* is present but infrequent in this zone. While total *Picea* influx is relatively low, there is a slight trend towards increasing rates (Fig. 11a). *Picea* stomates are occasionally present (Fig. 11b). PARs of Ericaceae, Poaceae, Cyperaceae and *Artemisa* are relatively high, although Ericaceae shows some variability within this zone (Fig. 11c). The presence of herb taxa is limited to a few key species such as *Rumex/Oxyria* and Rosaceae, which show relatively low influx rates. Fern and moss types are relatively abundant, with particularly high PARs of *Lycopodium annotinum*, *Sphagnum* and undifferentiated monolete spores. The influx rates of *Pediastrum* is relatively high while *Isoetes* spores show low PARs. Other aquatic taxa such *Potamogeton* and *Sparganium-Typha* occur occasionally in this zone (Fig. 11d).

Pollen sub-zone SBL IIB (~5000 to 3500 ^{14}C yrs BP / 515 cm to 480 cm): Pollen influx of total *Picea* increases from about 500-600 grains/cm^2*yr to about 1000 grains/cm^2*yr. During the same interval, *P. mariana* becomes a more important part of the assemblage but *P. glauca* remains dominant. Spruce macrofossils are present and are particularly abundant between 4200 ^{14}C yrs BP to 3800 ^{14}C yrs BP (495 cm and 485 cm). *Alnus* PARs remain high while the influx rates of other shrub and herb taxa decline. Ericaceae influx rates become more variable and range between <20 grains/cm^2*yr to almost 60 grains/cm^2*yr. A gradual decline of PARs is also noted in all fern and moss taxa and is most prominent in *Sphagnum*. *Isoetes* influx rates slightly increase while those of *Pediastrum* rapidly decline. Apart from *Isoetes*, all other aquatic taxa reduce to zero values as early as 4300 ^{14}C yrs BP (500 cm).

Pollen sub-zone SBL IIA (~3,500 to 1,500 ^{14}C yrs BP/ 480 cm to 425 cm): Total *Picea* influx rates remain high until 2000 ^{14}C yrs BP (440 cm) while macrofossils are abundant throughout this zone. There is a sharp decline across all terrestrial taxa shortly after the deposition of Jarvis Ash (479-485cm), starting around 3500 ^{14}C yrs BP (480 cm), with the exception of *Picea*. The decline in PARs particularly affects Ericaceae and

Artemesia as well as some moss and fern types. Although lowered PARs are observed for most fern and moss types, *Equisetum* becomes more abundant after 3,200 ^{14}C yrs BP (475 cm). *Isoetes* PARs continue to increase, while other aquatic taxa are virtually absent.

Pollen sub-zone SBL I (~1,500 ^{14}C yrs BP to present / 425 cm to 379 cm): Total *Picea PARs* are lowered compared to the previous period. Stomates and needles are occasionally present in this zone, specifically between 500 and 300 ^{14}C yrs BP (395 cm to 385 cm). *Alnus* and *Betula* influxes slightly increase to around 1000 grains/cm^2*yr while *Salix* PARs are somewhat variable. The influx rates of all shrub taxa is higher than in Zones SBL IIA and IIB but does not reach the elevated values observed in Zone III. Influx rates of important herb taxa such as *Ranunculaceae* and *Rumex/Oxyria* remain fairly low while Rosaceae types show slightly increased frequencies. Other herbs such as Caryophyllaceae, Brassicaceae and Onagraceae, that are not present in previous zones become more important in zone SBL I. *Lycopodium annotinum* influx rates significantly increase in zone SBL I. There is also a slight increase in *Sphagnum* PARs. Monolete spores show a slight increase, with *Dryopteris* becoming more frequent. The most significant change in this pollen zone is the major rise of *Isoetes* PARs, which shift from less than 500 grains/cm^2*yr to values between 750 and 1000 grains/cm^2*yr while other aquatic taxa remain almost absent. There is a decline in influx rates across all taxa in the top 10 cm of the core, which most likely reflects dilution effect due to the watery consistency of the surface sediments.

Interpretations

A combined record of pollen, macrofossil and stable isotope analysis indicates that significant changes occurred at Swampbuggy Lake during the past 6,750 ^{14}C yrs BP. These reported results suggest that the overall productivity was much higher before 5,000 ^{14}C yrs BP. Shrubs, such as *Betula*, *Salix* and *Alnus* dominate the pollen assemblage between 6,750 ^{14}C yrs BP and 5,000 ^{14}C yrs BP implying that the vegetation around Swampbuggy Lake consisted primarily of open shrub-tundra. The presence of *Artemisia* and *Juniperus* reflects drier climate conditions and a fairly open landscape during this interval. *Picea* may have been scarce on the landscape but was not

completely absent. Since spruce stomates are present in the core, scattered individuals of *Picea* were located in close proximity to the lake. Elevated carbon content and $\delta^{13}C$ values in the carbon isotope record suggest that productivity in Swampbuggy Lake was fairly high during the period between 6,750 ^{14}C yrs BP and 5,000 ^{14}C yrs BP, probably as a result of relatively high summer temperatures that enhanced conditions for photosynthesizing organisms in the lake water. Lake water depth may have been shallower during this period, improving the growth of macrophytes, which would have contributed to the increase in carbon stable isotopes. Apart from slightly elevated C/N ratios, there is no clear evidence for increased macrophyte growth. *Isoetes* pollen PARs are relatively low while other aquatics are only infrequently present in the record.

The drop in carbon stable isotopes starting around 5,000 ^{14}C yrs BP corresponds to a decline in lake productivity, mostly likely as a function as a function of climate deterioration. The lake remains in a state of relatively low productivity during the interval from 3,800 ^{14}C yrs BP to 2,000 ^{14}C yrs BP indicating a period of cooler climate. Increased *Picea* influx rates as well as stomate and needle frequencies suggest that *Picea* was invading the landscape around the lake. Increased moisture may have favored the growth of *Picea*. Although *P. mariana* becomes a more part of the pollen assemblage, it does not dominate the total stomate frequencies. Increased influx of *P. mariana* pollen may be the result of increased growth of *P. mariana* in the lower areas of the Susitna Valley, while *P. glauca* still dominated the landscape in the upland region around Swampbuggy Lake. Declining influx rates of herb taxa, heath, as well as mosses and ferns suggests that the vegetation transformed from a shrub-tundra into a forest-tundra. The response of spruce at Swampbuggy Lake is contrary to what is expected at a treeline site during a shift towards cooler climate. Despite lowered temperatures, increased moisture may have triggered the expansion of spruce. Lake-level studies from Central Alaska indicate that moisture levels did not reach modern values until after 6,000 ^{14}C yrs BP (Edwards et al., 2001). This suggests that prior to 5,000 ^{14}C yrs BP, spruce at Swampbuggy lake may have been drought-stressed but was to able to take advantage of increased moisture levels after that time.

The carbon stable-isotope record suggests two periods of climate amelioration indicated by episodes of slightly higher lake productivity between 2000 ^{14}C yrs BP and 800 ^{14}C yrs BP. This period is also marked by declining *Picea* influx rates and a

simultaneous increase in *Alnus*, *Betula* and Ericaceae, which is most prominent after 1500 ^{14}C yrs BP. The vegetation around Swampbuggy Lake may have changed from a dense forest-tundra to a more open spruce woodland type vegetation. The stomate record indicates that spruce remained on the landscape in this region, however. The appearance of herb taxa such as Onagraceae, Caryophyllaceae and Brassicaceae may indicate episodes landscape destabilization and greater disturbance regimes. The significant increase in *Isoetes* after 1500 ^{14}C yrs BP may indicate changes in lake-levels and/or lake productivity (Edwards et. al, 2000). *Isoetes* prefers clear water, which suggests that Swampbuggy Lake may have shifted towards generally more oligotrophic conditions during the past 2,000 to 1,500 ^{14}C yrs BP.

A brief interval between 800 ^{14}C yrs BP and 200 ^{14}C yrs BP indicates a period of low productivity in Swampbuggy Lake, which may be linked to the LIA. Within the limits of the core chronology, the timing appears to be synchronous to several LIA cooling events seen in glacial and tree-ring records. The terrestrial vegetation did not undergo any significant changes, suggesting that the vegetation around Swampbuggy Lake has been fairly stable during the this period. The δ^{13}C record suggests that lake productivity may have been increasing during the past century. Tree-ring data indicates that tree recruitment has been most prominent during the past 60 years (Figs. 24a and 24b).

Summary

A multi-proxy record of pollen, macrofossils and stable isotopes from Swampbuggy Lake indicates major changes during the Mid- to Late-Holocene. While the period from 6,750 14C yrs BP until 5,000 ^{14}C yrs BP was characterized by a more xeric shrub-tundra environment, a transformation to forest-tundra and expansion of spruce took place as early as 5000 ^{14}C yrs BP as climate became cooler and wetter. The landscape reverted again to more open woodlands by 1500 ^{14}C yrs BP. Carbon stable isotopes suggest that lake productivity was relatively high during a short episode from 1,500 to 800 ^{14}C yrs BP. The cooling events of the Little Ice-Age resulted in decreased productivity in Swampbuggy Lake but had no detectable effect on the vegetation surrounding the lake.

CHAPTER 3: NUTELLA LAKE

Introduction

Nutella Lake (unofficial name, N63°03', W147°25') is a small kettle pond (~2 ha) that most likely formed after the last glacial retreat approximately 14,000 to 12,000 yrs ago. The lake is located an elevation of 931 m in the upland region between the upper Nenana valley to the west and the upper Susitna River valley to the east (Fig. 1). The topography of this area is characterized by smoothly rolling hills and hummocks composed of glacial debris. The vegetation surrounding the Nutella Lake (NL) is dominated by a mesic shrub and heath tundra mixture. Very few trees of *Picea glauca* are scattered around the lake, most of which are small and show stunted appearance. Krummholz spruce is also found in the vicinity of lake. Occasional stands of taller, upright growing trees are confined to moist lower lying gullies in close proximity to the lake (Fig. 12).

Nutella Lake is composed of two basins, which are separated by a shallow sill. The basins are approximately 8-10 m across and have water depths of 965 cm (A) and 465 cm (B). Nutella Lake is an open basin lake. It has two small inlets to the south and a small creek draining the lake to the northeast (Fig. 12). Water chemistry measured in the deeper basin in the July and September 1996 showed that the lake is thermally stratified and that bottom waters approach anoxia (DO=0.88µg/l) during the summer months. The secci depth measured was ~5.4 m. No measurements were made for the shallower basin but it is likely that stratification occurs in the shallower part as well. Due to the steepness of the deeper basin and the subsequently high probability of sediment slumping, data used in this discussion derives mainly from the shallow basin core (Core NLB). Core NLB was retrieved from the deepest part of the basin at a water depth of 4.65 m. Core depth is reported relative to the lake water interface.

Results

Sedimentology. The sediment is composed of mainly dark brown organic sediments that are rich in silty clay material (Fig. 13). The sediment package from 675 cm to 595

cm is partially banded. Bands are ~ 1-2 cm width and consist of lighter and darker brown layers. A significant change in lithology occurs above Jarvis Ash (590-595 cm). The lower transition between Jarvis Ash and the organic fraction of the sediment is relatively sharp while the upper layers of the tephra layer gradually blend into the unit above. Charcoal and macrofossils are abundant intermittently between 590 to 560cm. The upper half of the core consists of more homogenous sections that are lacking the bands seen in the lower part of the core. The transition between 495 cm and 485 cm is characterized by extremely high abundance of sandy to silty, coarse-grained material. Lithological changes at Nutella Lake are fairly similar to those of Swampbuggy Lake (see Chapter 2).

Age chronology. Four AMS radiocarbon dates were obtained at 1000 to 2000 yrs intervals in Core B of Nutella Lake (Table 2). Spruce needle were used as a material for dating at all levels. The age-depth curve shows an excellent fit with an R^2 value of 0.99 (Fig. 14). The base of the core has an approximate age of 6,780 ^{14}C yrs BP.

Table 2: Radiocarbon dates from Nutella Lake.

	Depth [cm]	Age [yrs BP]	+/-	Material	Lab	Lab#
top	***465***	**0**		top		
^{14}C AMS	***508-510***	**1230**	**60**	spruce needle	L. Livermore Nat.Lab.	56430
^{14}C AMS	***566-568***	**2980**	**50**	spruce needle	INSTAAR/NOSAMS	10375
^{14}C AMS	***590-595***	**3650**	**150**	Jarvis Ash	(see Beget, 1994)	
^{14}C AMS	***620-622***	**4730**	**50**	spruce needle	L. Livermore Nat.Lab.	56431
^{14}C AMS	***672-675***	**6750**	**130**	spruce needle	L. Livermore Nat.Lab.	56432

Magnetic susceptibility and LOI analysis. Magnetic susceptibility follows closely the sediment lithology at Nutella Lake. High susceptibility signals occur at levels where terrestrial material such as silt and ash layers is predominant (Fig. 15). Loss-on-ignition

(LOI) shows high variability at 500°C in Nutella Lake Core B (Fig. 15). The organic matter content, measured as % weight loss at 500°C, varies between 3% and 27%. Most values range between 15 and 20%, however. Low values are usually found at levels with increased terrestrial influx, e.g. silt layers or tephra layers. LOI values at 500°C slightly increase between 600 cm and 500 cm. However, no significant long-term trend can be observed in the data. LOI values at 850°C are extremely low and exhibit only minor changes. This indicates that inorganic carbon in the form of carbonates is not present in the core in large quantities.

Stable isotope analysis. Nutella Lake exhibits a wide array of C/N values that range between 9 to >14. Compared to Swampbuggy Lake, average C/N ratios are slightly elevated (~11 to 12) but are still within the range of material of aquatic origin (Fig. 16a). Some samples with high C/N shows tendencies of being of terrestrial origin as their C/N and $\delta^{13}C$ values fall within the range of values seen from soils around the lake ($\delta^{13}C$ -28 to -26‰). There is a weak inversed correlation between the carbon content of the sediment and $\delta^{13}C$ values (Fig. 16b). Relatively high abundances of organic carbon tend to be accompanied by relatively low $\delta^{13}C$ values. Low $\delta^{13}C$ ratios are also observed from a few samples that fall outside the main cluster, and correspond to layers with low-organic content in the core. The complex relationship between the carbon content in the sediment, C/N ratios and $\delta^{13}C$ values indicates that the isotopic signal of the sediment organic matter is affected by multiple controls. Thus, the carbon isotopic record from Nutella Lake may be influenced by both changes in carbon source, as well as changes in the isotopic composition of organic matter produced in the lake. Organic matter types in Nutella Lake include aquatic material that used ^{13}C-depleted DIC ($\delta^{13}C \leq$ -26‰ and C/N ≤12), aquatic organic matter that utilized ^{13}C- enriched DIC ($\delta^{13}C \geq$ -26‰ and C/N ≤12) and terrestrial material ($\delta^{13}C \sim$ -26‰ and C/N ≥12) (Fig. 16a). Carbon isotopes at Nutella Lake are strongly influenced by lithological changes in the core. The presence of silt or tephra layers are accompanied by $\delta^{13}C$ values typical for soils and plants surrounding the lake, indicating increased input of terrestrial matter to this small sized lake.

Carbon isotopes at Nutella Lake display a wide range of values varying from –22 to -29‰ (Fig. 17). Values are especially low at the base of the core and in the uppermost

sediments. While $\delta^{13}C$ exhibits a trend of increasing values between roughly 6,780 ^{14}C yrs BP to 2,500 ^{14}C yrs BP (675 cm to 555 cm), C/N ratios gradually decline during the same period. Increased carbon content in the sediment (10-12%) suggests higher levels of productivity during a period from 6780 ^{14}C yrs BP to 5,000 ^{14}C yrs BP (675 cm to 625 cm). Increased utilization of a heavily depleted carbon source by phytoplankton, such as CO_2 from soil respiration, may have contributed to the light isotope ratios in the sediment.

$\delta^{13}C$ ratios are particularly variable between 5,000 ^{14}C yrs BP to roughly 3,000 ^{14}C yrs BP (625 cm and 570 cm). During this period, C/N ratios decline, indicating that the supply of allochthonous carbon source has diminished. The lake may have used a larger supply of $CO_{2(air)}$, which adds a to ^{13}C-enriched carbon source. Carbon content in the sediment is generally lower than during the previous period, which may indicate an overall generally lowered productivity. However, the sediment lithology suggests a relatively short episode of high productivity shortly after the deposition of Jarvis Ash. During a period from 3,000 ^{14}C yrs BP to 1,500 ^{14}C yrs BP, C/N ratios slightly increase ranging between 10-12. $\delta^{13}C$ ratios average to -26‰. Productivity may have been lowered during this interval.

A significant change in carbon supply occurs around 1500 ^{14}C yrs BP when C/N ratios abruptly increase to higher values (~12 to 13) (Fig. 17). This trend is associated with elevated abundance of carbon in the sediment while $\delta^{13}C$ values remain between –24‰ to –26 ‰. Between 600 ^{14}C yrs BP and the core top, $\delta^{13}C$ values gradually decrease. The uppermost part of the sediment core is characterized by low C/N ratios and very low $\delta^{13}C$ values which suggests a ^{13}C-depleted carbon source contributed to the lake's DIC pool. Productivity is difficult to determine as changes in the carbon source occurred. Productivity may have been lower during the past 300 ^{14}C yrs BP due to of LIA cooling.

Nitrogen isotopes at Nutella Lake vary between –2.5‰ and +2‰ (Fig. 18). There is a significant trend towards declining $\delta^{15}N$ values between 6,780 ^{14}C yrs BP and 3,000 ^{14}C yrs BP (675 to 565 cm) while $\delta^{15}N$ ratios climb again towards higher values again after 3,000 ^{14}C yrs BP (Fig. 18). A positive correlation exists between $\delta^{15}N$ and C/N while no correlation exists between $\delta^{15}N$ and the nitrogen content in the sediment (Fig. 19a

and 19b). Thus, the nitrogen isotopic signature at Nutella Lake may reflect the relative input of aquatic and terrestrial of organic matter to the lake. The interval of low $\delta^{15}N$ ratio between 4,000 ^{14}C yrs BP and 3,000 ^{14}C yrs BP may be linked to increased input of aquatic organic matter to the lake. Alternatively, the decrease in $\delta^{15}N$ during an interval from 4,000 ^{14}C yrs BP and 3,000 ^{14}C yrs BP may also be the result of changes in the nitrogen cycling in the lake. The absence of anoxia in the hypolimnion, due to a lack of stratification during times of unfavorable climate conditions, may result in reduced nitrogen transformation processes at the sediment water interface that usually generate ^{15}N-enriched nitrogen compounds.

Pollen and macrofossils. Pollen percentages from Nutella Lake are shown in Fig. 20. Spruce and shrubs dominate the assemblage. Increased abundances of *Picea* occur between 630 cm and 500 cm (5,200 ^{14}C yrs BP to 5,000 ^{14}C yrs BP), while *Betula* percentages gradually decline starting around 630 cm. As mentioned earlier in Chapter 2, pollen accumulation rates (PAR) measured as grains/cm^2*yr, combined with the macrofossil record, provide a more accurate picture of the vegetation changes around the lake. Nutella Lake influx rates were divided intro three major and two minor pollen zones using statistical analysis (CONISS) and visual evaluation of the diagrams (Fig. 21 a-d).

Pollen Zone Nutella Lake III (6,750 to 4,100 ^{14}C yrs BP / 675 cm to 600 cm): This zone shows relatively high total influx rates. *Picea* PARs fluctuate but start to increase around 5500 ^{14}C yrs BP (525 cm) from less than 100 to at least 300 grains/cm^2*yr. Relatively high PARs are also observed across all major terrestrial and aquatic taxa. The herb assemblage at Nutella Lake is limited to very few abundant taxa, most importantly *Rumex/Oxyria* and Ranunculaceae.

Pollen Zone Nutella Lake II (4,100 to 1,500 ^{14}C yrs BP / 600 cm to 520 cm): Decreased PARs are common features of this pollen zone. Decreased values are most prominent for *Salix* and Ericaceae, as well as monolete and trilete spore types, while this decline is less pronounced for *Sphagnum*. Relatively high PARs persist for aquatic taxa, specifically *Pediastrum*, and important herb taxa. Rosaceae becomes a more frequent component of the herb assemblage. *Picea* PAR are still highly variable but are somewhat higher compared to the earlier interval.

Pollen Zone Nutella Lake IB (1,500 to 500 ^{14}C yrs BP / 520 cm to 485 cm): A sharp increase in PARs occurs around 1500 ^{14}C yrs BP (520 cm). This increase is closely associated to a rather abrupt change in terrestrial influx seen in the C/N ratios (see isotope section). Hence, these influx rates may reflect increased pollen inwash rather than increased productivity on the landscape.

Pollen Zone Nutella Lake IA (500 ^{14}C yrs BP to present / 485 cm to 465 cm): Total *Picea* influx rates decline starting around 600 to 500 ^{14}C yrs BP (490 cm to 485 cm). Influx rates of shrub taxa appear to be slightly higher than in zone NL II. PARs of Ericaceae and Poaceae slightly increase. *Artemisia* PARs and other herb taxa present a mixed signal with variable influx rates but are generally more frequent than in the previous zone. *Sphagnum* PARs remain at a relatively constant level while declining influx rates are observed for other spore taxa and aquatic taxa. A dilution effect of the uppermost sediments, as observed at Swampbuggy Lake, is not likely in Nutella Lake because the PARs do not change simultaneously for all taxa at the core top. Furthermore, C/N ratios have declined, indicating that the PARs may not affected by increased pollen inwash during this period.

Interpretations

A major change at Nutella Lake occurs between 5,000 ^{14}C yrs BP and 1,500 ^{14}C yrs BP. The lake experiences significant lithological changes that are coupled with a shift from a predominately terrestrially driven to a mixed terrestrial-aquatic system. The carbon content in the sediment suggests that productivity was higher before 5,000 ^{14}C yrs BP and gradually declined after that most likely due to climate deterioration.

Before 4,000 ^{14}C yrs BP, the vegetation around Nutella Lake was a mixed shrub-heath tundra and dominated by *Alnus*, *Betula* and *Salix* and Ericaceae as well grasses and sedges. This pollen assemblage and the presence of *Artemisia* suggests that the vegetation consisted of a mixture of xeric and mesic communities. High pollen accumulation rates indicate dense vegetation cover and a fairly productive plant community. *Picea* was present on the landscape as early as 6,750 ^{14}C yrs BP, as indicated by the stomate record. Trees must have been scarce, however, since stomate frequencies are low. *Picea* PARs gradually increase between 5,000 ^{14}C yrs BP and

4,000 ^{14}C yrs BP, suggesting that spruce becomes increasingly important on the landscape during this interval. Around 4000 ^{14}C yrs BP, a decline can be observed across all terrestrial taxa except *Sphagnum*. The decline most severely affects Ericaceae as well as *Lycopodium* types. The more consistent presence of spruce macrofossils, particularly between 4000 ^{14}C yrs BP to 3,000^{14}C yrs BP, indicates that *Picea* became a more important component of the vegetation around Nutella Lake, even though total *Picea* PARs are somewhat variable during the same interval. As at Swampbuggy Lake, the expansion of spruce coincides with a period when climate in this region was becoming cooler and moisture as indicated by independent climate proxy records (Calkin and Wiles, 1991; Edwards et al., 2001; isotopes in this study). In general, the period from 4,000 ^{14}C yrs BP and 1,500 ^{14}C yrs BP marks a time of landscape stabilization at Nutella Lake, which is also seen in the isotope record by a decrease in terrestrial influx to the lake. *P. mariana* constitutes a large part of the total *Picea* influx while no *P. mariana* macrofossils have been noted at this site at any time. This implies that *Picea* influx rates may represent a regional rather than a local signal and that some proportion of spruce pollen possibly derived from lower lying valleys.

From 1,500 ^{14}C yrs BP to 500 ^{14}C yrs BP, the carbon isotope record may have been complicated by a change in carbon source that reflects a local change in sedimentary processes. Higher δ^{13}C ratios may suggest that lake productivity was increased, possibly as a result of climate amelioration. Nutella Lake shows a period of high C/N ratios, which abruptly increased around 1,500 ^{14}C yrs BP. This change in terrestrial influx was accompanied by a simultaneous increase in pollen influx rates. Total PARs may indicate a productive spruce woodland and shrub-tundra vegetation community, but the actual pollen signal may have been distorted by increased pollen inwash into the lake. The high influx in terrestrial material is most likely all or part of a local phenomenon that is independent from regional climate fluctuations.

By 600 ^{14}C yrs BP, the vegetation around Nutella Lake had reverted to a shrub-tundra dominated landscape. *Picea* decreased in importance while Ericaceae, Cyperaceae, Poaceae and herb taxa become more abundant compared to the period before 1,500 ^{14}C yrs BP. *Alnus* and *Betula* PARs slightly increase, indicating that shrubs remain an important part of the of the vegetation community. No spruce macrofossils are present in the uppermost sediments of the core, although a few small trees are located

near the lake today. As these small trees have developed during the 20th century from krummholz bases of unknown age, it is possible that individuals were scattered around Nutella Lake during the past 500 ^{14}C yrs BP.

Summary

Significant change at Nutella Lake occurred during the past 6,780 ^{14}C yrs BP. Spruce has been on the landscape since the beginning of the record but became more dominant after 5,000 ^{14}C yrs BP. Between 5,000 ^{14}C yrs BP to 3,500 ^{14}C yrs BP, the vegetation around Nutella Lake shifted from a shrub and heath dominated community to an open spruce woodland. The expansion of spruce coincides with a period of probable climate deterioration. While cooler temperatures may have persisted during this period, increased moisture availability may have been favorable to spruce growth. Changes occur simultaneously in both the lake and terrestrial ecosystem. Nutella Lake experienced decreased influx of allochthonous carbon as a result of landscape stability between 5,000 ^{14}C yrs BP to 3,500 ^{14}C yrs BP. Around 600 ^{14}C yrs BP to 500 ^{14}C yrs BP the landscape reverted to a shrub-tundra dominated vegetation. Lake productivity was low during much of the past 500 ^{14}C yrs, indicating that Nutella Lake may have responded to the cooling events of the LIA.

CHAPTER 4: DISCUSSION AND CONCLUSIONS

Paleolimnological changes in the north-central Alaska Range

The isotope records from Swampbuggy and Nutella Lakes illustrate the complexity of carbon and nitrogen cycling in lakes and the difficulty of deciphering paleolimnological histories. This study suggests that the detailed history of individual lakes may vary, depending on bathymetry, hydrology and the vegetation within the watershed. However, climate fluctuations probably dictate the long-term trends in the isotope data.

The isotope history of Swampbuggy and Nutella Lakes can be divided into three distinct stages. Carbon isotope ratios from the two lakes are significantly different until 4,500 ^{14}C yrs BP (Fig. 22b). While $\delta^{13}C$ values at Swampbuggy Lake are relatively high and range from –27‰ to –21‰, Nutella Lake exhibits relatively low values averaging around –26‰ to –28‰. C/N ratios are slightly elevated during this period but do not suggest that terrestrial input was dominant in either lake (Fig. 22a). $\delta^{13}C$ values and carbon accumulation rates suggest that Swampbuggy Lake was moderately to highly productive during this period (Fig. 23). $CO_{2(air)}$ was probably the main source to the lake's DIC, adding a significant amount of heavy carbon to the lake. The significantly lower values at Nutella Lake (~ -27‰) may be a due to a large amount of ^{13}C-depleted CO_2 entering the lake water. CO_2 derived from soil respiration rather than $CO_{2(air)}$ may have been a more important carbon source. Due to the very small size and open basin hydrology, Nutella Lake was much more susceptible to changes in the carbon source than Swampbuggy Lake. Lake water $\delta^{18}O$ and DH values from surface sediments indicate that Nutella Lake has a lower water residence time than Swampbuggy Lake (Table 3), i.e. water entering the lake is flushed through the system more quickly.

Starting around 4,500 ^{14}C yrs BP the carbon isotopic signal at Swampbuggy Lake drastically decreases (Fig. 22b). This event is concurrent with elevated influx rates of *Picea* pollen that are related to the increased density of the spruce forest around the lake. Moister climate and cooler summer temperature may have resulted in reduced productivity and lower $\delta^{13}C$ values. In addition, the flux of ^{13}C-enriched atmospheric CO_2 to the lake may have been diminished as the sequestering of carbon was reduced in

times of low productivity. The decline in $\delta^{13}C$ ratios at Swampbuggy Lake is accompanied by a continued trend of increasing $\delta^{13}C$ values at Nutella Lake. As climate deteriorated, soil respiration may have slowed down and thus, decreasing the input of heavily depleted carbon to the lake. Therefore, lake water CO_2 may have been closer to equilibrium with the atmosphere in both lakes.

During an interval between 3,500 ^{14}C yrs BP and 1,500 ^{14}C yrs BP, which coincides with higher spruce densities, the range of $\delta^{13}C$ values is similar at both lakes. This indicates that Swampbuggy Lake and Nutella Lake have shifted towards systems, dominated by aquatic organic matter. Lowered carbon accumulation rates indicate that productivity was low at both lakes (Fig. 23).

Significant differences in carbon cycling between the two lakes are observed after 1,500 ^{14}C yrs BP. While C/N ratios at Swampbuggy Lake remain fairly low, a drastic increase of C/N ratios occurred at Nutella Lake around 1,500 ^{14}C yrs BP (Fig. 22a), which indicates a sharp increase of terrestrial organic matter to the lake. Soils from Nutella and Swampbuggy Lake generally have intermediate $\delta^{13}C$ values (-28‰ to -26‰) and bring ^{13}C-depleted allochthonous matter to the lake. Despite the increased influx of terrestrial material to the lake, $\delta^{13}C$ ratios at Nutella Lake between 1,500 ^{14}C yrs BP and 800 ^{14}C yrs BP are relatively high. This suggests that productivity at Nutella Lake must have been increased during this time in order to overprint the depleted $\delta^{13}C$ signature of the carbon source. Higher productivity is also inferred at Swampbuggy Lake, which exhibits increased $\delta^{13}C$ ratios. This suggests that improved climate conditions prevailed during this period from 1,500 ^{14}C yrs BP and 800 ^{14}C yrs BP.

A decline in $\delta^{13}C$ ratios at Swampbuggy and Nutella Lake suggests lowered productivity during an interval from 800 ^{14}C yrs BP to 200 ^{14}C yrs BP. This may signal the onset of cooler climate in this region during the Little Ice-Age. At Nutella Lake, *Picea* influx rates declined after 500 ^{14}C yrs BP, while tundra species have gained in importance.

Based on ^{210}Pb dating, $\delta^{13}C$ values at Swampbuggy Lake have gradually increased during the past ~100 years (Fig. 22b). This suggests that climate conditions at Swampbuggy Lake may have improved during the past century resulting in increased productivity in the lake. Lowered C/N ratios at Nutella Lake indicate a change in carbon

cycling at least during the past 100 years. The pronounced effect of lowered $\delta^{13}C$ ratios at Nutella Lake may reflect higher input of ^{13}C-depleted CO_2 from increased soil respiration processes due to a warmer climate. Nitrogen stable isotopes ratios from both study sites do not show any significant trends (Fig. 22c). This may suggest that nutrient cycling was either constant throughout time or that both system have not been N-limited and thus, were not sensitive to changes in N-cycling.

Table 3: Swampbuggy and Nutella Lake water chemistry.

	COND (µS)	pH	DO (mg/l)	SiO2 (mg/l)	TP (µg/l)	TN:TP	DOC	CHLa
SBL	8.00	8.13	12.93	0.16	10.60	38.00	205.00	0.7
NL	82.00	7.30	13.20	7.45	5.70	52.00	7.60	<0.1

	*1996**		*1997**	
	$\delta^{18}O$	DH	$\delta^{18}O$	DH
SBL	-14.39	-125.74	-12.96	-125.23
NL	-19.64	-149.66	-19.74	-157.84

(all data from Gregory-Eaves et al., 2000, except * from B. Finney , unpublished data)

In summary, the results from Swampbuggy and Nutella Lakes show that both lakes responded to a major climate shift at the transition from the Mid- to the Late-Holocene. Productivity was lowered from 3,500 ^{14}C yrs BP and 1,500 ^{14}C yrs BP during a period of colder and probably moister conditions. A brief episode of improved climate conditions followed between 1,500 ^{14}C yrs BP to 800^{14}C yrs BP. Climate fluctuations between 800 ^{14}C yrs BP to 200 ^{14}C yrs BP, related to the LIA, were less pronounced but may have resulted in reduced productivity changes in both lakes. Based on the composition of organic matter, conditions during the most recent century are similar to those between 6750 ^{14}C yrs BP and 5,000 ^{14}C yrs BP.

Vegetation changes in the north-central Alaska Range during the Mid- to Late-Holocene

Few data have been published from the mountain regions of Central Alaska. The pollen records presented from Swampbuggy and Nutella Lake indicate changes in the treeline vegetation during the past 6,700 ^{14}C years BP. The density of *Picea* was higher during a period from 5,000 to 2,000 ^{14}C years BP at both sites. Increased effective moisture may have improved conditions for spruce growth in the dry upland areas of the Alaska Range. While spruce growth is related to summer temperatures, studies from higher elevation sites in northern Alaska and northwestern Canada have shown that growth is also dependent on precipitation (Garfinkel and Brubaker, 1980; Szeicz and MacDonald, 1996). Lake-level studies from Central Alaska indicate that moisture levels had not reached modern values by Mid-Holocene times (Edwards et al., 2001). Therefore, drier conditions before 5,000 ^{14}C yrs BP may have limited the growth of spruce in the upland region of the north-central Alaska Range. Experimental studies transplanting of *P. glauca* in the Arctic tundra suggests that survivorship of spruce can be high despite low temperatures. Survival rates are also dependent on the specific type of tundra, with more highly productive shrub-tundra having a more positive effect than a less productive heath tundra (Hobbie and Chapin, 1998). The interaction of cooler and moisture climate after 5,000 ^{14}C years BP may have affected spruce growth both directly and indirectly by having a negative effect on tundra taxa while shifting the competitive balance in favor of spruce. The record indicates that scattered individuals of both *P. glauca* and *P. mariana* were growing around Swampbuggy and Nutella Lake as early as 6,750 ^{14}C years BP but probably became an important component of the landscape no sooner than 5,000 ^{14}C years BP. As indicated by its absence from the macrofossil record at Nutella Lake, *P. mariana* probably never reached the limit of trees. However, it was able to establish in lower lying areas.

The increase in spruce density at Swampbuggy and Nutella Lakes is analogous to increases in *Picea* percentages observed at Tangle Lakes (Ager and Sims, 1981). However, the onset of spruce expansion at Tangle Lakes does not commence until approximately 3,500 ^{14}C years BP, a delay of at least 1,500 ^{14}C years BP between the sites. The temporal difference may be due to an inaccurate chronology from Tangle Lakes. Only two radiocarbon dates from bulk organic matter were obtained for the

Tangle Lake core, compared to eight AMS dates from Swampbuggy Lake during the same interval. In addition, the Tangle Lakes have a complex hydrology that could have led to variable sedimentation rates in the lake. At this point, this is the most likely explanation for the discrepancy between these records.

Other higher elevation pollen records from the Alaska Range, such Ten Mile Lake (Anderson et al., 1994), Eight Mile Lake (Ager, 1983) or Wonder Lake (Anderson et al., 1994) do not suggest any significant vegetation changes during the past 6,000 ^{14}C yrs BP, which may be due the low sampling resolution of the cores at these sites. In contrast, a high-resolution pollen record from Windmill Lake, which is located in the northern foothills of the Alaska Range approximately 160 m below treeline (Fig. 1), provides evidence that *Picea*, *Alnus* and *Betula* abundances fluctuated during a period between 5,800 and 3,000 ^{14}C yrs BP (Bigelow and Edwards, 2001). These oscillations may be associated with changes in the boreal forest. If this assumption holds true, the dynamics of spruce in the sub-alpine zone of the Alaska Range may be also reflect of a larger-scale response that affected the closed boreal forest of Central Alaska.

Pollen influx rates indicate that spruce densities have been declining during the past 2,000 to 1,500 ^{14}C yrs BP at Swampbuggy Lake. The frequent presence of macrofossils suggests, however, that spruce remained a major component of the landscape around the lake, although tree densities may have declined. At Nutella Lake, lowered spruce influx rates and the absence of spruce macrofossils indicate that treeline may have been lowered during the past 500 ^{14}C yrs BP, possibly as a result of LIA cooling. The absence of macrofossils is characteristic for lakes in the alpine tundra zone (Pisaric et al., 2000). If alpine tundra is defined as the zone above treeline but including tree species limit, Nutella can be described as an alpine tundra lake, even though a few small trees occur at the site today. Observations on modern trees indicate that spruce at Nutella Lake may have adapted to LIA cooling by phenotypically by changing from an upright growth form to layered Krummholz during times of unfavorable climate. Tree-ring data suggests that new tree recruitment occurred at both, Swampbuggy and Nutella Lake during the past century, and that spruce has responded positively to 20th century warming (see Appendix B).

Synthesis: Climate reconstruction for the past 6,750 ^{14}C years BP in Central Alaska

The stable isotope record provides an independent measures for paleoclimate and, combined with the vegetation record, gives a better understanding of climate variations. Table 4 summarizes distinct climate intervals as a function of lake productivity changes and indicates vegetation response.

Table 4: Reconstruction of paleoclimate variations in the mountain regions of Central Alaska during the Mid- to Late- Holocene.

INTERVAL	^{14}C yrs BP	Climate	Paleoclimate Proxy Information	
			relative lake productivity	vegetation
I	0 200	initially cool, followed by warming trend	increasingly high	shrub tundra/open forest tundra, increased *Picea* recruitment during last century in sub-alpine zone
II	200 800	cold/moist	low	possibly lowered treeline at higher elevation
III	800 1500	warmer/drier intervals within cooling trend	higher	declining spruce densities
IV	1500 5000	cool/moist	lowered	increasing spruce densities of both *P. glauca* and *P. mariana*; dense forest-tundra at lower elevation
V	5000 <6800	warm/ dry but increasingly moist	high	xeric/mesic shrub-heath tundra to open forest- tundra, scattered spruce; *P.glauca* dominant

An overall trend towards colder and moister climate can be observed during the past 5,000 ^{14}C yrs BP. The presence of *Juniperus* and the greater abundance of *Artemesia* indicate dry, open microsites may have been widespread, supporting the reconstruction of a drier, more open tundra at this time. Higher lake productivity suggests higher mean summer temperatures before 5,000 ^{14}C yrs BP.

Between 5,000 ^{14}C yrs BP and 3,500 ^{14}C yrs BP, decreased summer temperatures resulted in lowered lake productivity. Elevated moisture levels apparently improved conditions for spruce growth. Spruce may have been drought-stressed as a result of warmer and drier climate before 5,000 ^{14}C yrs BP (Barber et al., 2000). As moisture levels increased in Central Alaska during Mid-Holocene times (Edwards et al., 2001), conditions may have become more favorable for spruce growth in the upland sites of the north-central Alaska Range. An expansion of both white and black spruce probably occurred at lower elevations, whereas white spruce densities increased at treeline.

Cooler and moist conditions persisted at least until 1,500 ^{14}C yrs BP. Advances of land-terminating and coastal glaciers are observed throughout Alaska during this time period (Calkin and Wiles, 1991). The region may have experienced episodes of warmer conditions during a period from 1,500 ^{14}C yrs BP to 800 ^{14}C yrs BP, as indicated by increases in lake productivity. The later part of this interval coincides with the Medieval Warm Period, which is recognized from the glacial record in southern Alaska (Calkin et al., 2001). The interval between 800 ^{14}C yrs BP and 200 ^{14}C yrs BP coincides with the LIA. This period is characterized by lowered lake productivity and lowering in treeline at higher elevation.

Age-structure analysis from tree-rings at both Swampbuggy and Nutella Lake suggests that spruce responded positively to a warming trend during the past century. Spruce recruitment has been relatively continuous at SB Lake in the 20th century. At Nutella, krummholz forms have generated vertical leaders in the 20th century and there is evidence of recent (~ past 30-40 yr) seedling and sapling recruitment around the lake. The warming trend during the past ~100 years can also be observed in the lake record and is associated with increased lake productivity. Conditions and carbon cycling in both lakes are now similar to those during the warm period before 5,000 ^{14}C yrs BP.

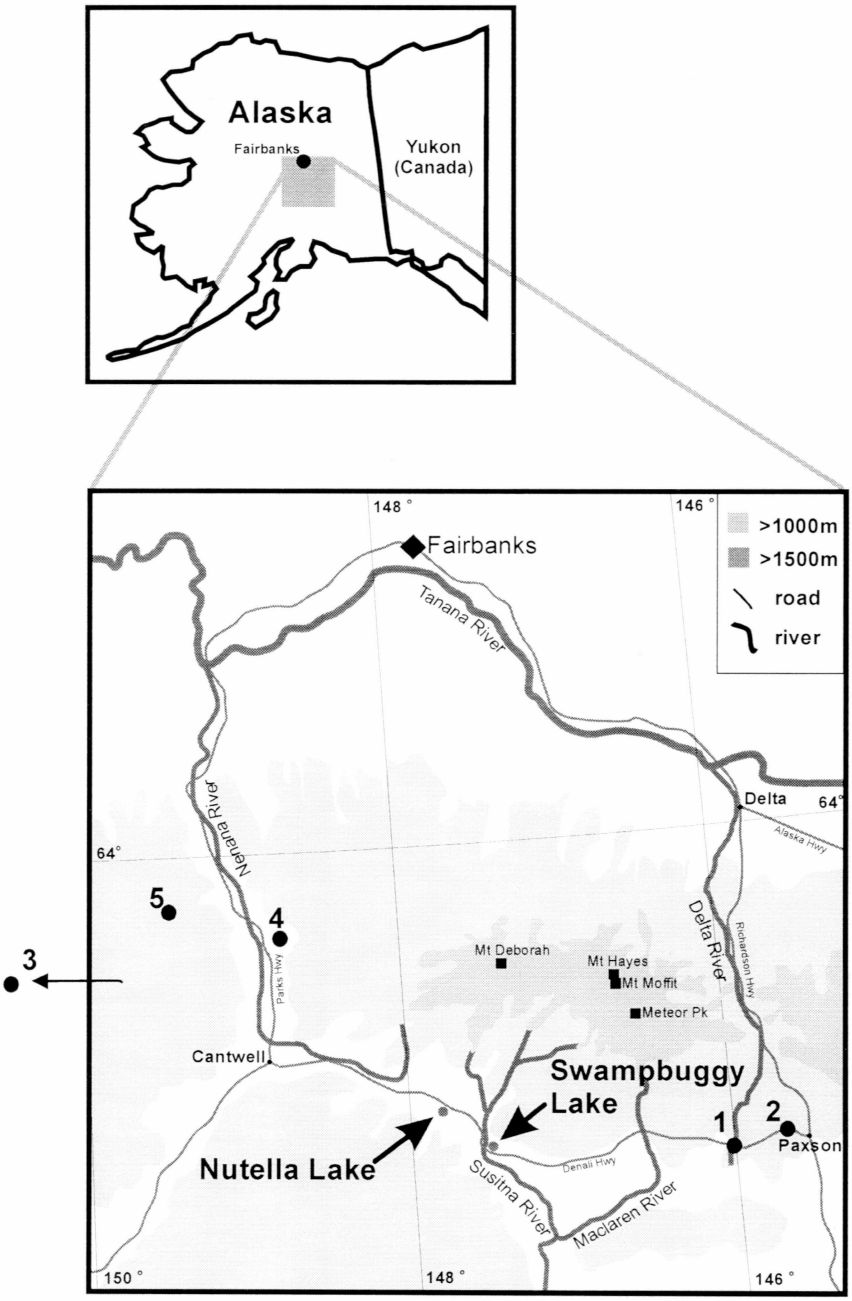

Fig. 1: Location of study area. Other sites mentioned in the text: 1=Tangle Lakes, 2=Ten Mile Lake, 3=Wonder Lake, 4=Windmill Lake, 5=Eight Mile Lake.

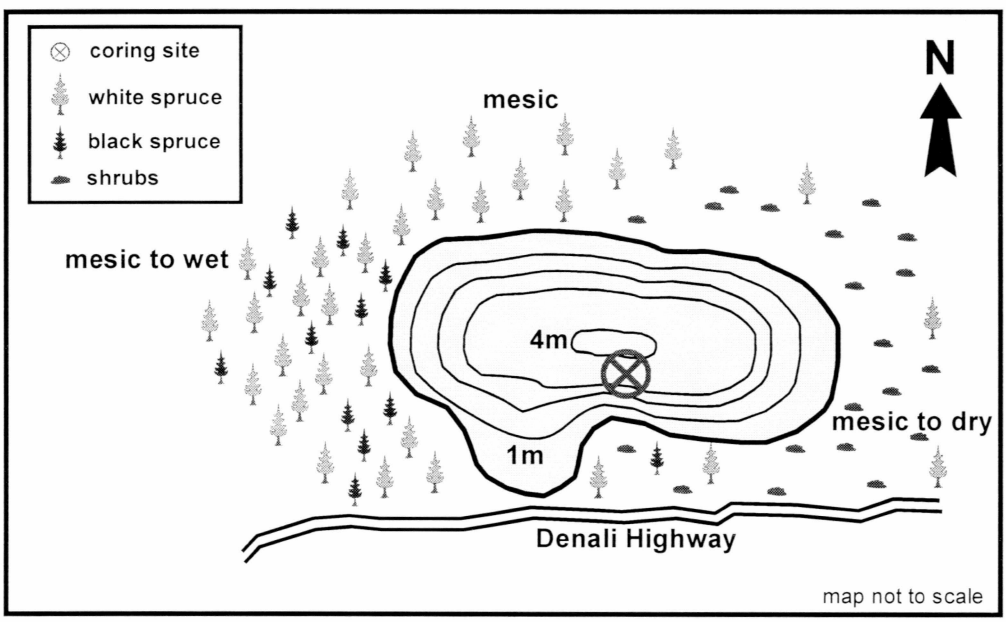

Fig. 2: Swampbuggy Lake bathymetry, coring site and landscape description.

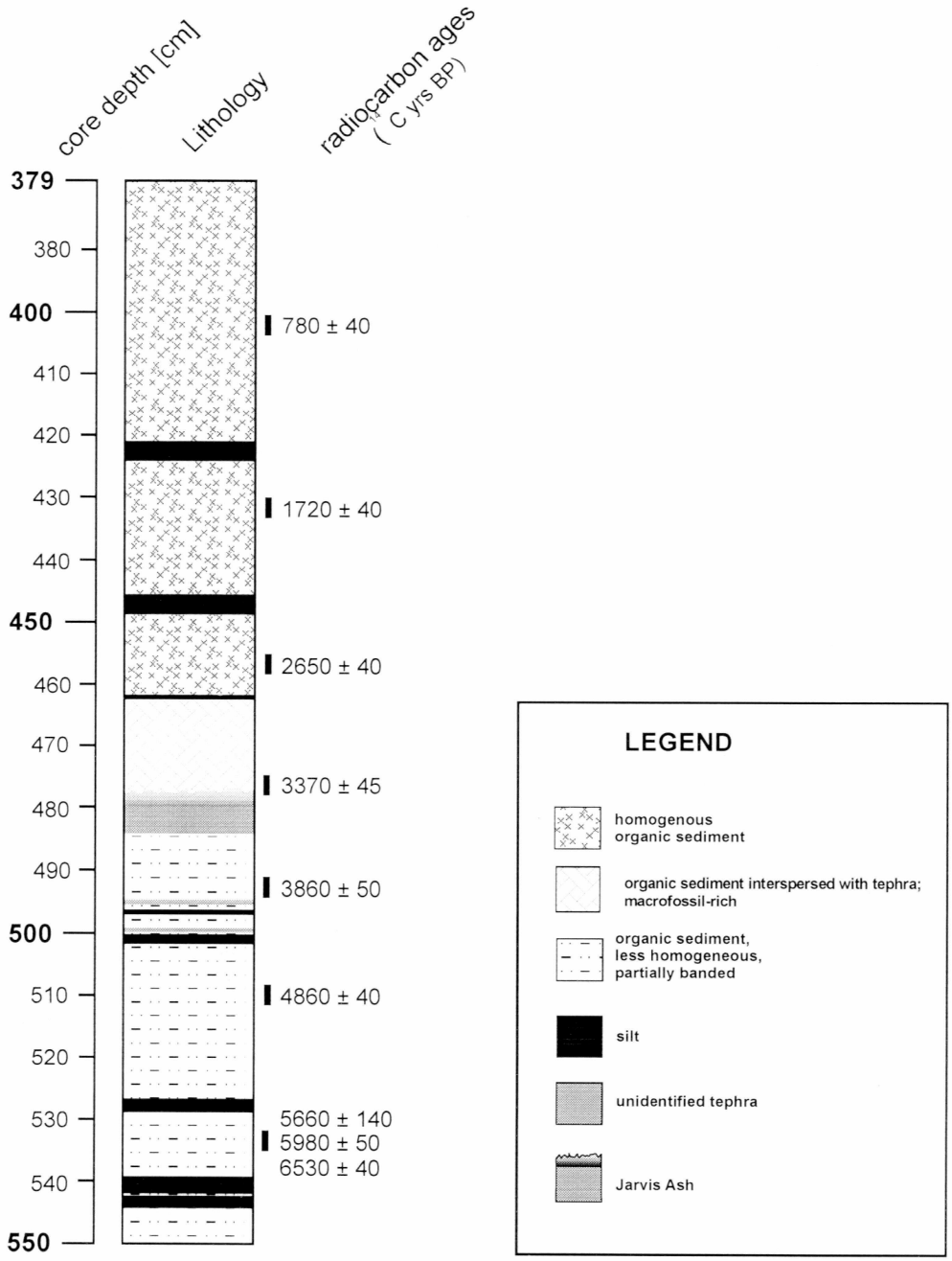

Fig. 3: Lithology and radiocarbon dates from Swampbuggy Lake.

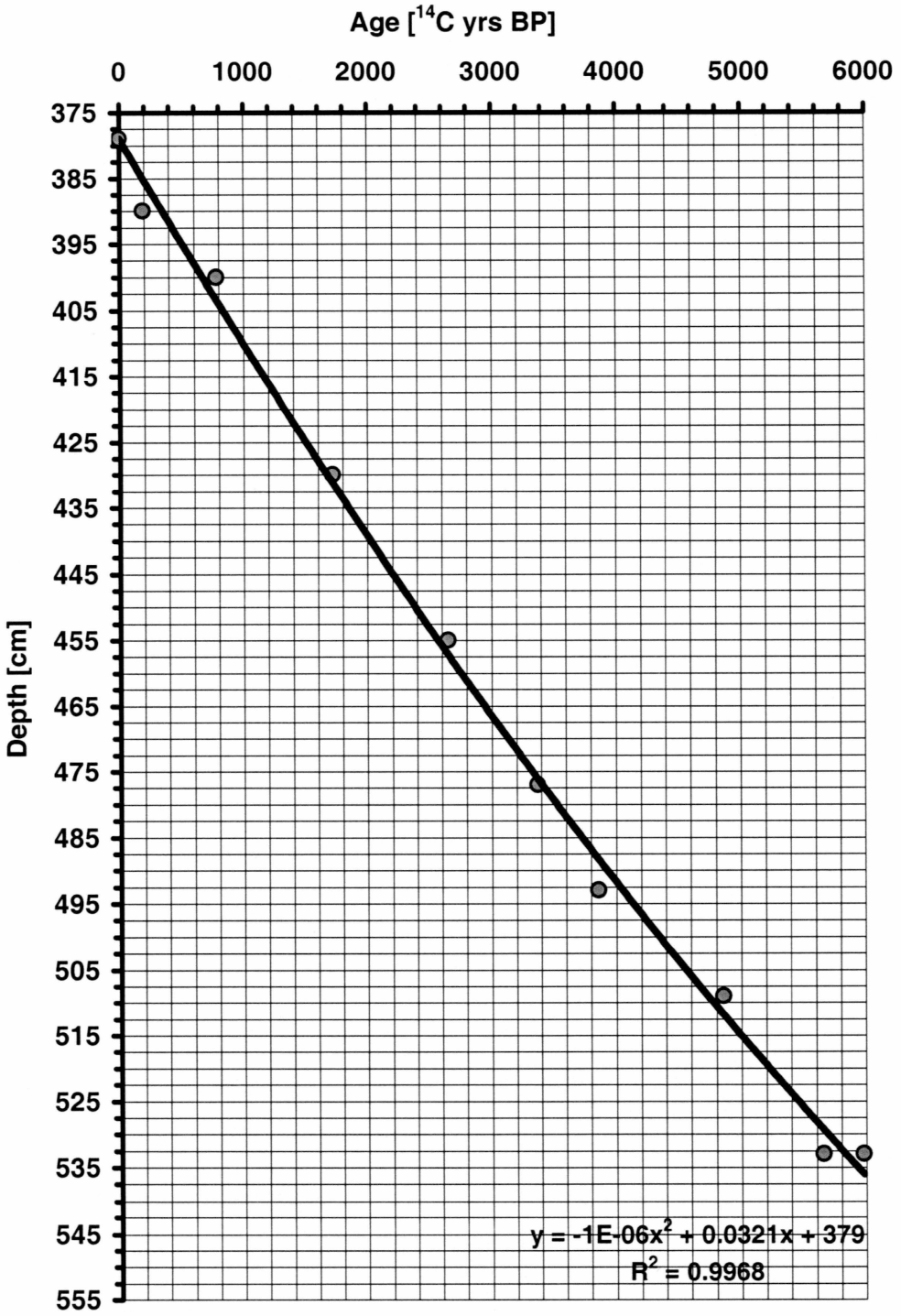

Fig. 4: Swampbuggy Lake age-depth chronology.

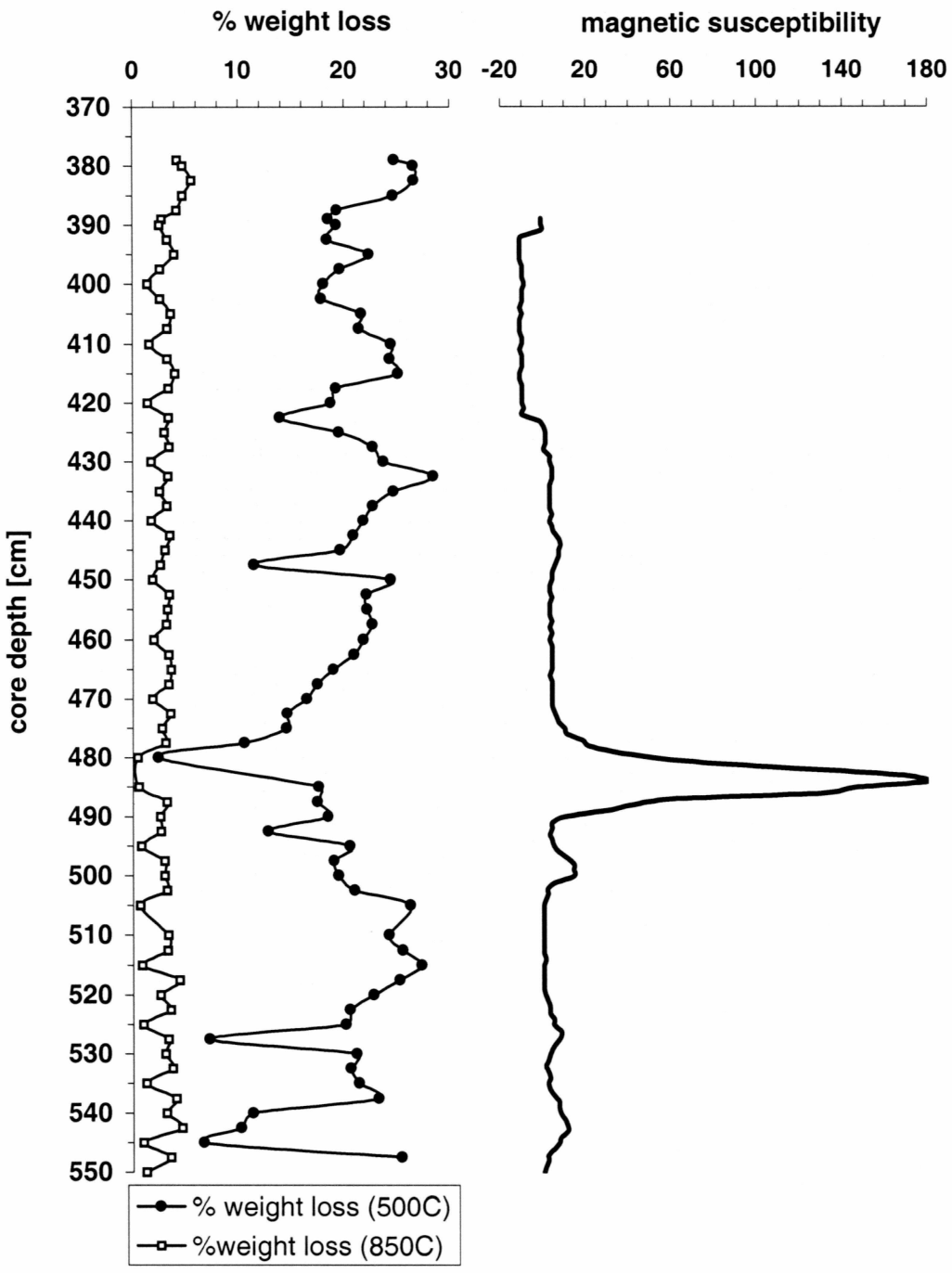

Fig. 5: LOI and magnetic susceptibility measurements from Swampbuggy Lake.

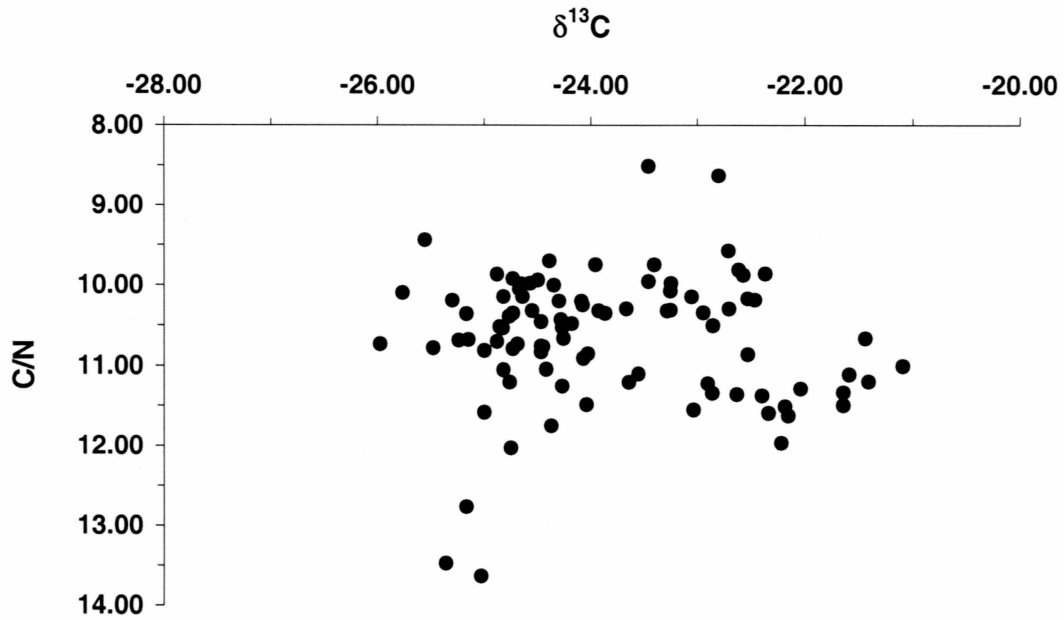

Fig. 6a: Correlation between $\delta^{13}C$ values and C/N from Swampbuggy Lake.

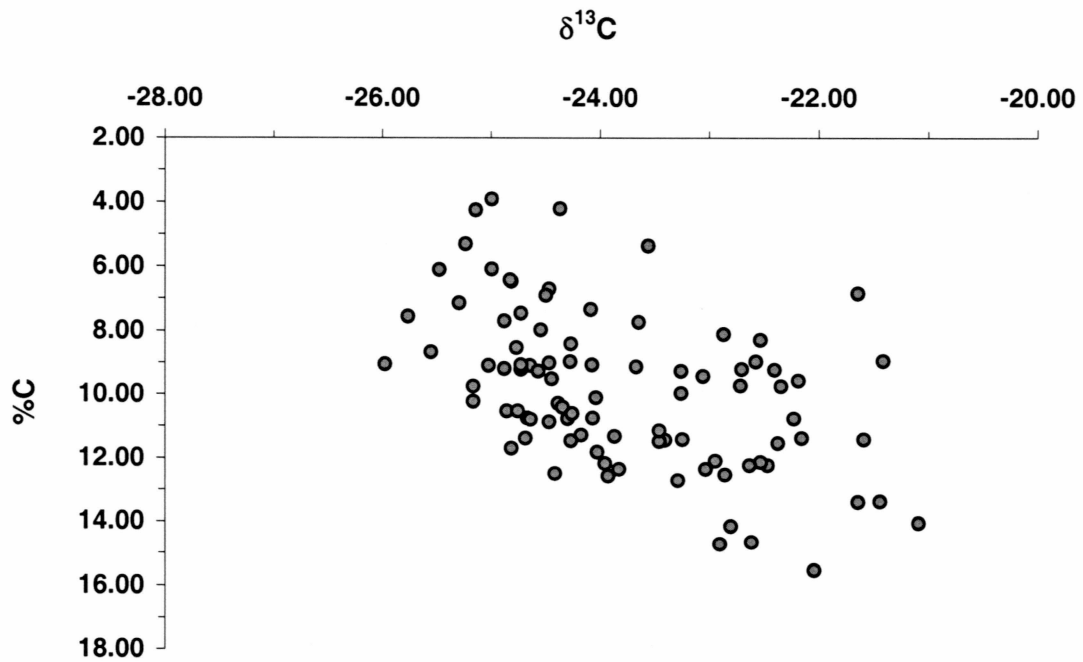

Fig. 6b: Correlation between $\delta^{13}C$ values and %C from Swampbuggy Lake.

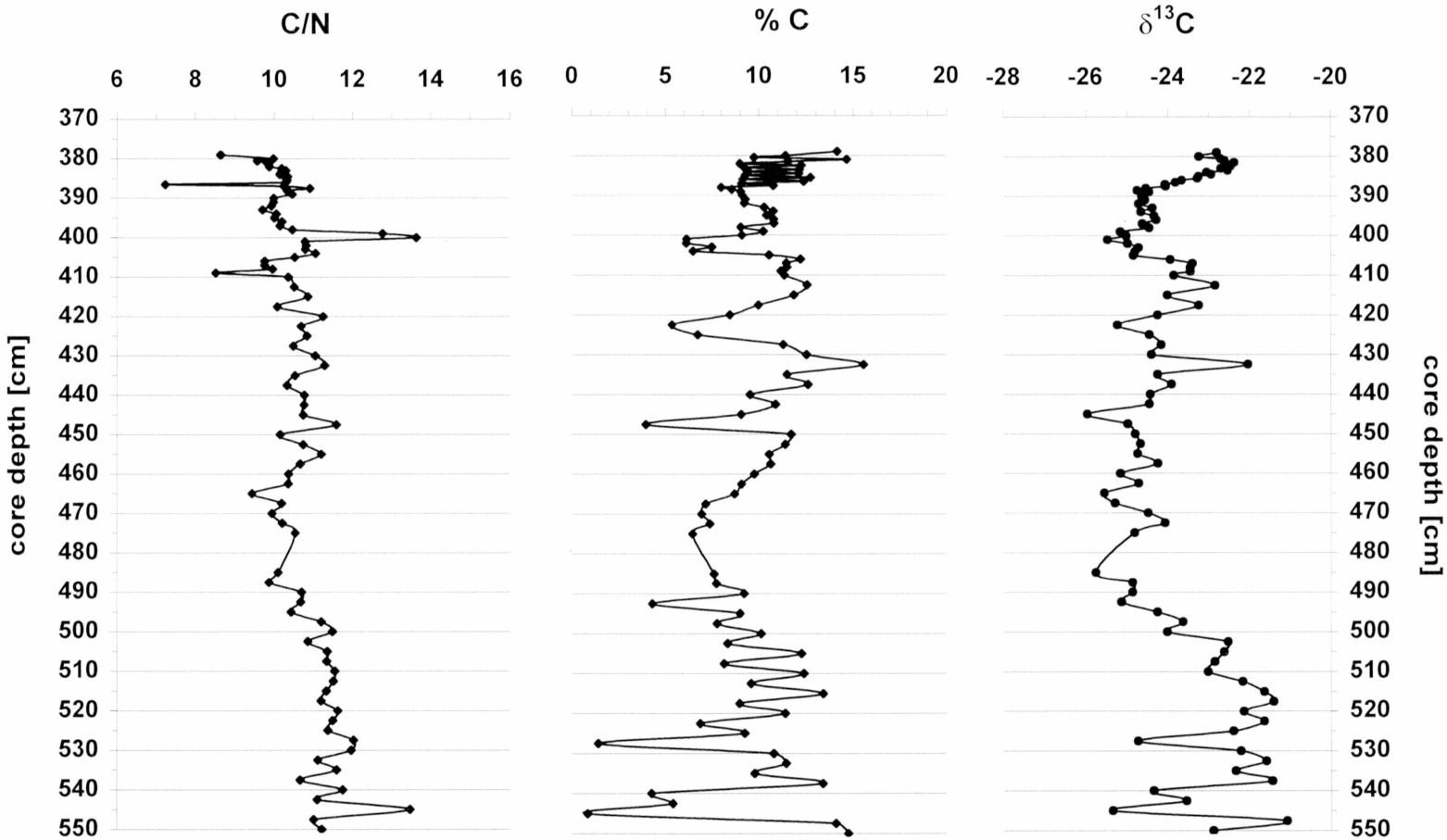

Fig. 7: A detailed diagram of carbon stable isotope data from Swampbuggy Lake.

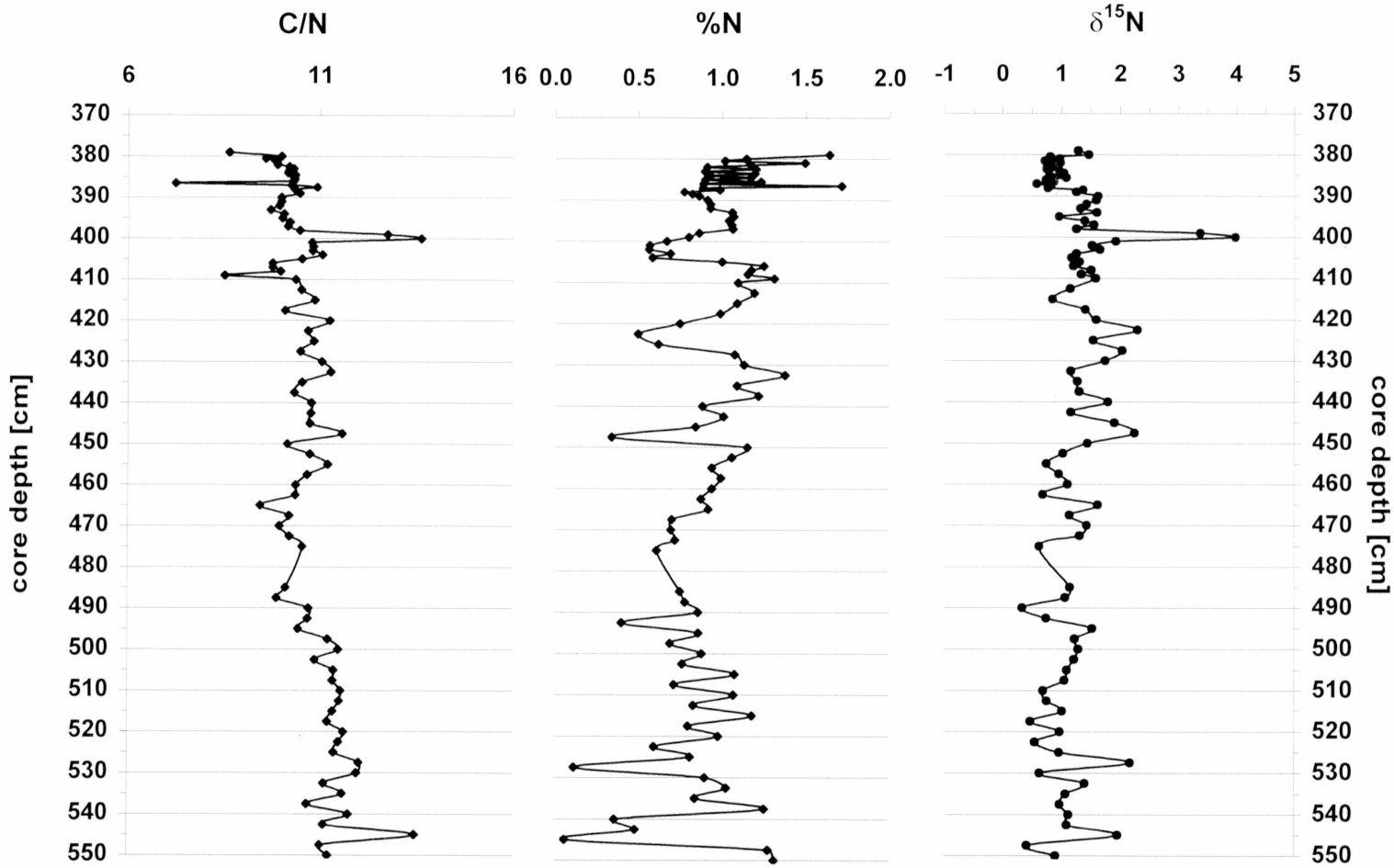

Fig. 8: A detailed diagram of nitrogen stable isotope data from Swampbuggy Lake.

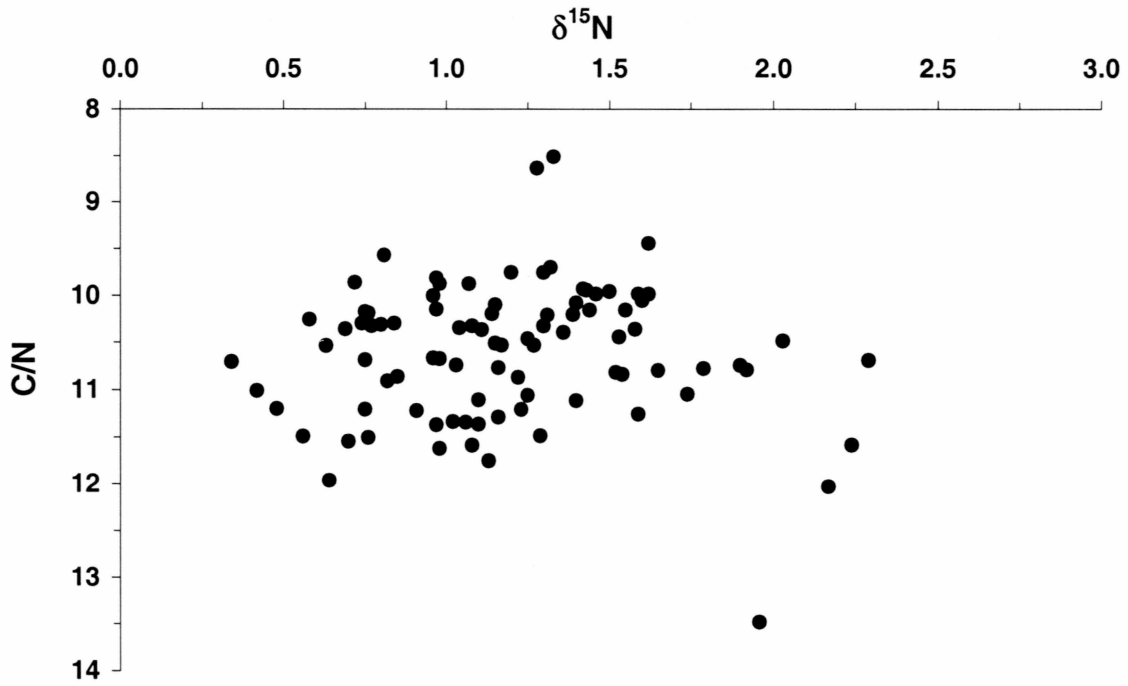

Fig. 9a: Correlation between $\delta^{15}N$ and C/N from Swampbuggy Lake.

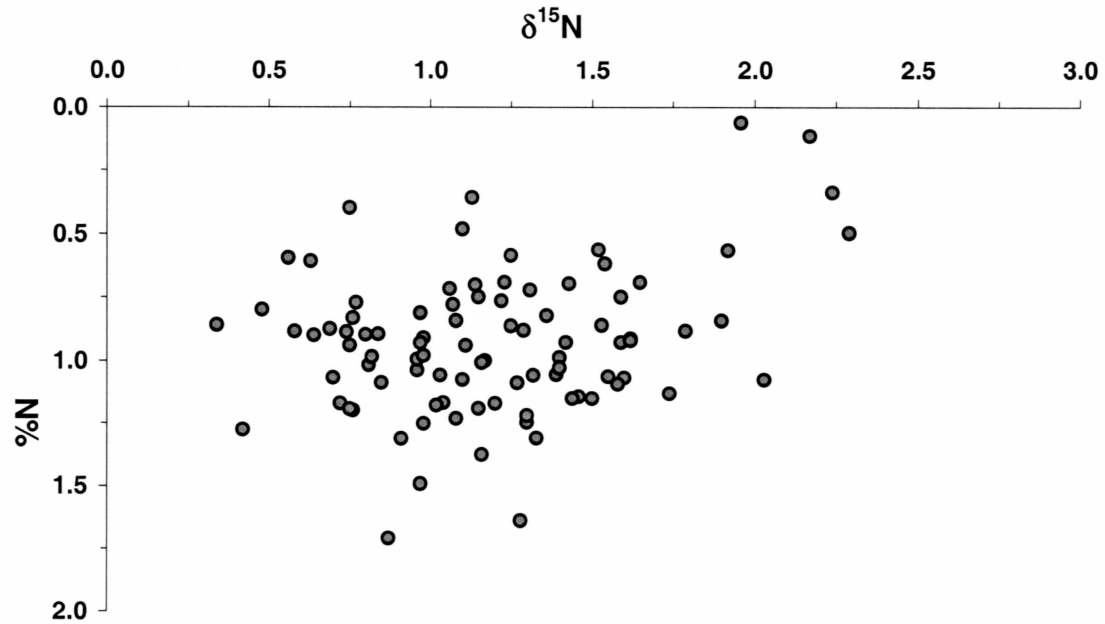

Fig. 9b: The relationship between $\delta^{15}N$ and the nitrogen content in Swampbuggy Lake.

Fig. 10: Swampbuggy Lake pollen percentages.

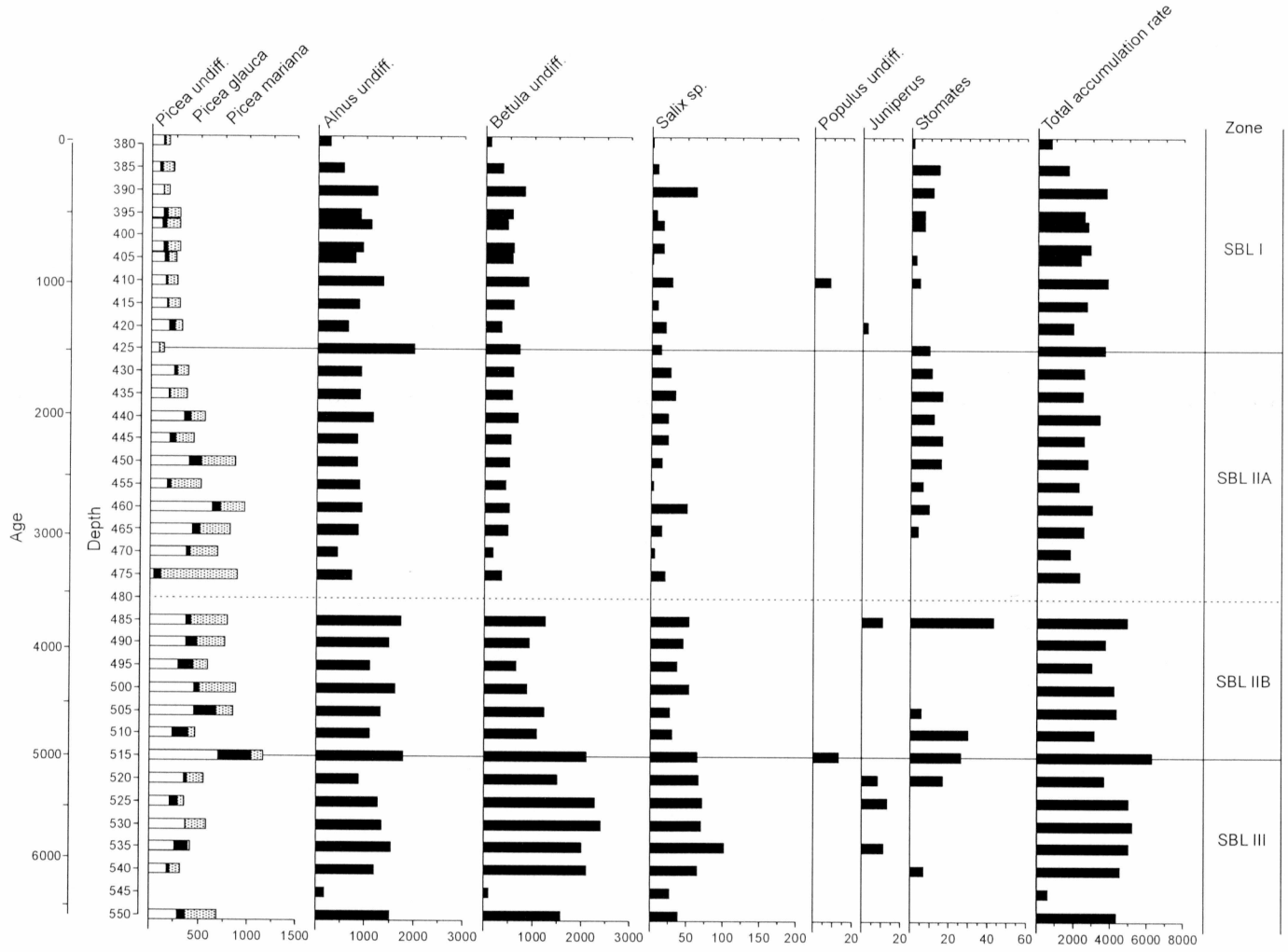

Fig. 11a: Swampbuggy Lake pollen influx diagram (trees and shrubs).

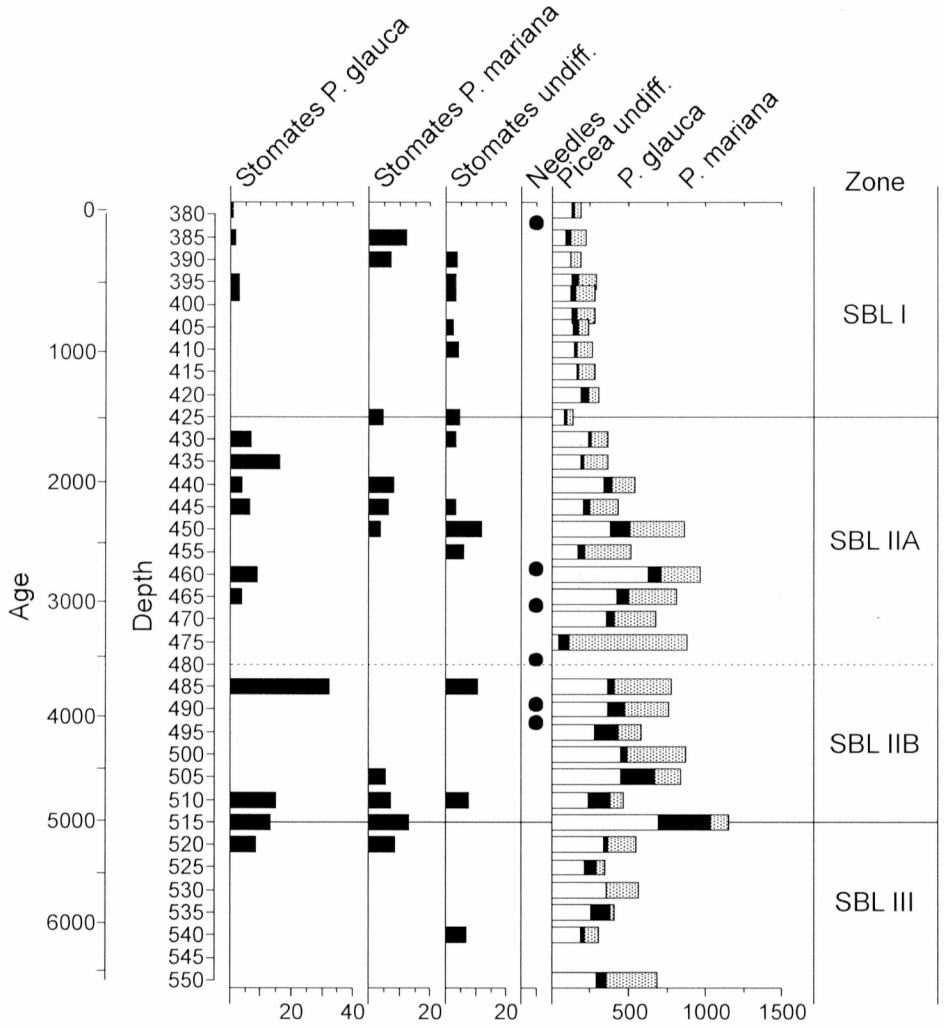

Fig. 11b: Swampbuggy Lake spruce pollen and macrofossil diagram.

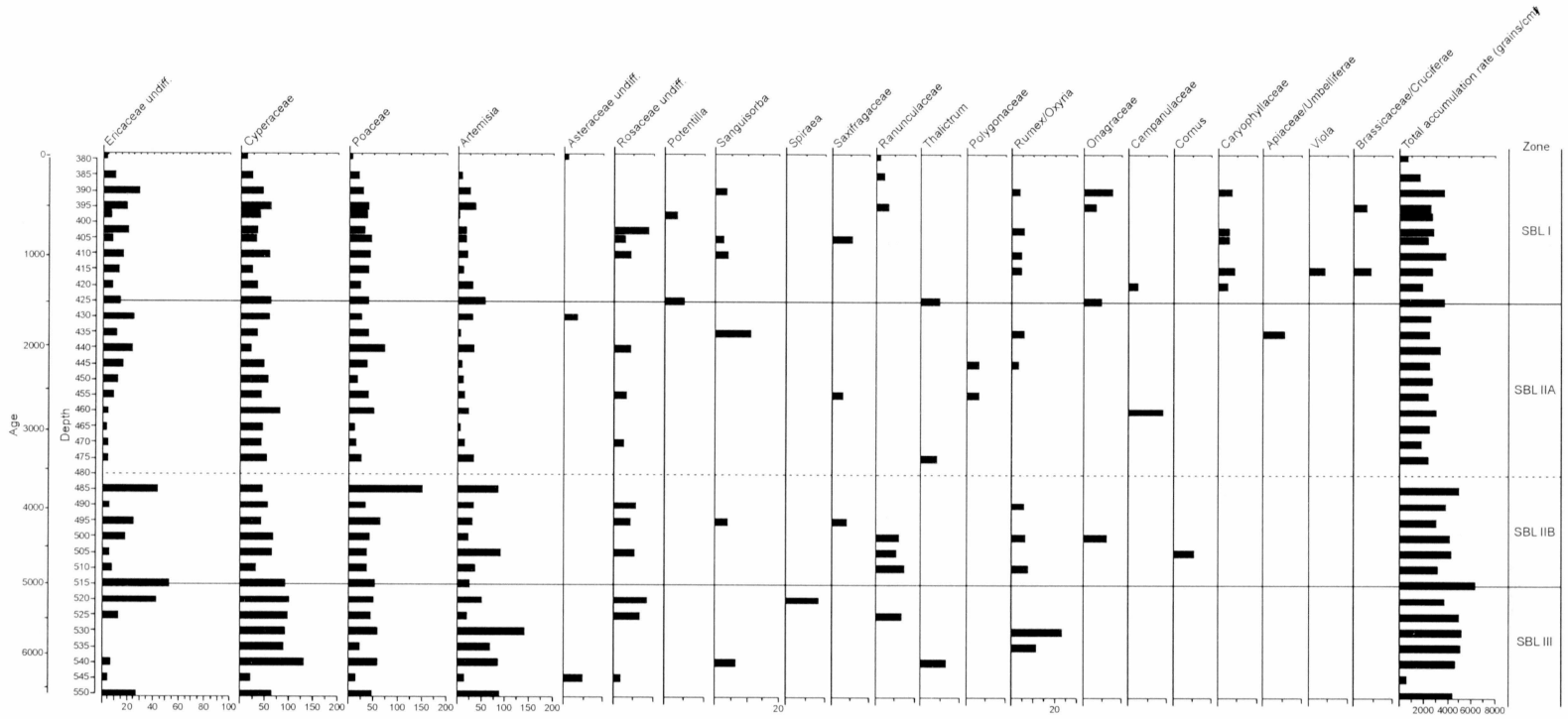

Fig. 11c: Swampbuggy Lake pollen influx diagram (herbs).

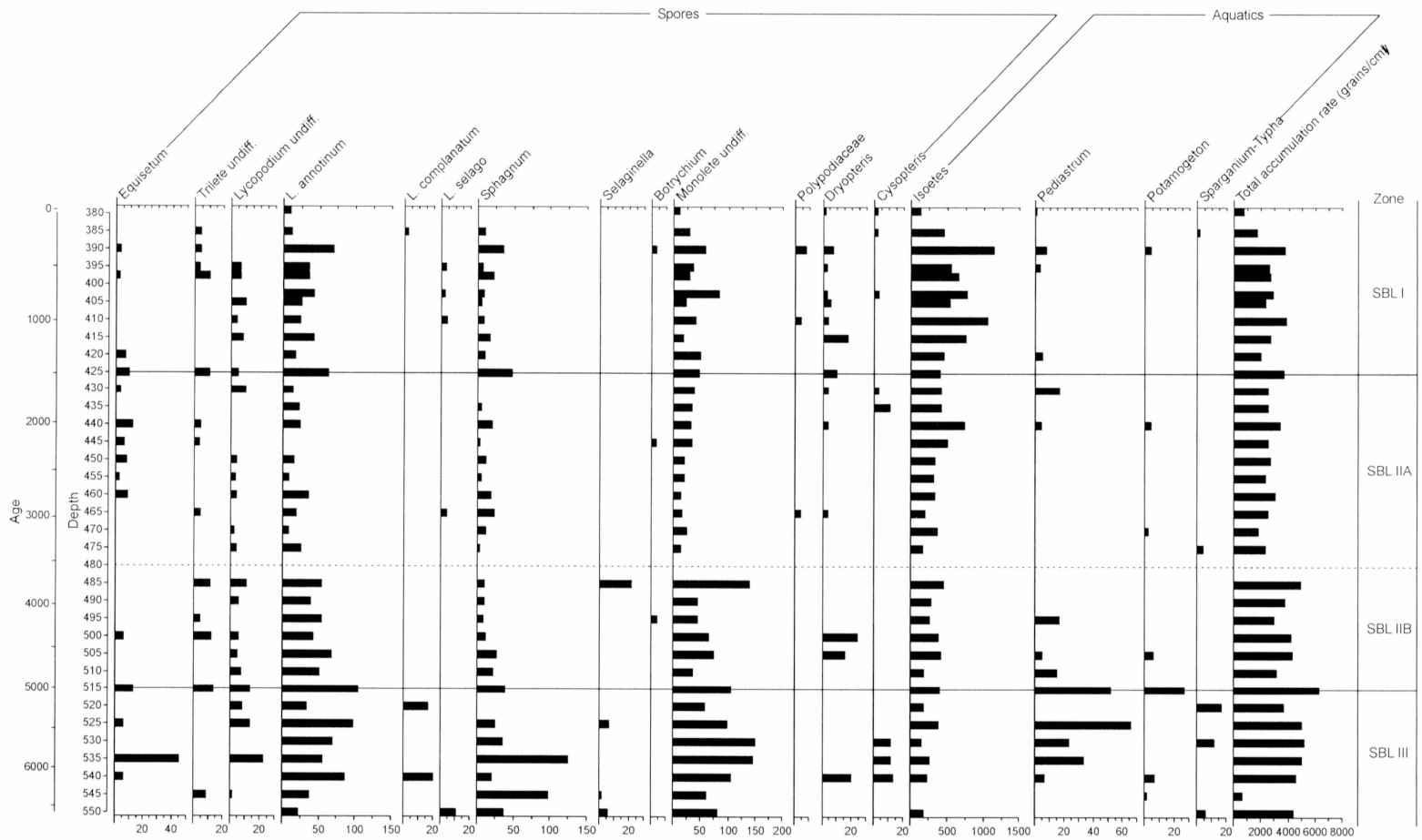

Fig. 11d: Swampbuggy Lake pollen influx diagram (spores and aquatics).

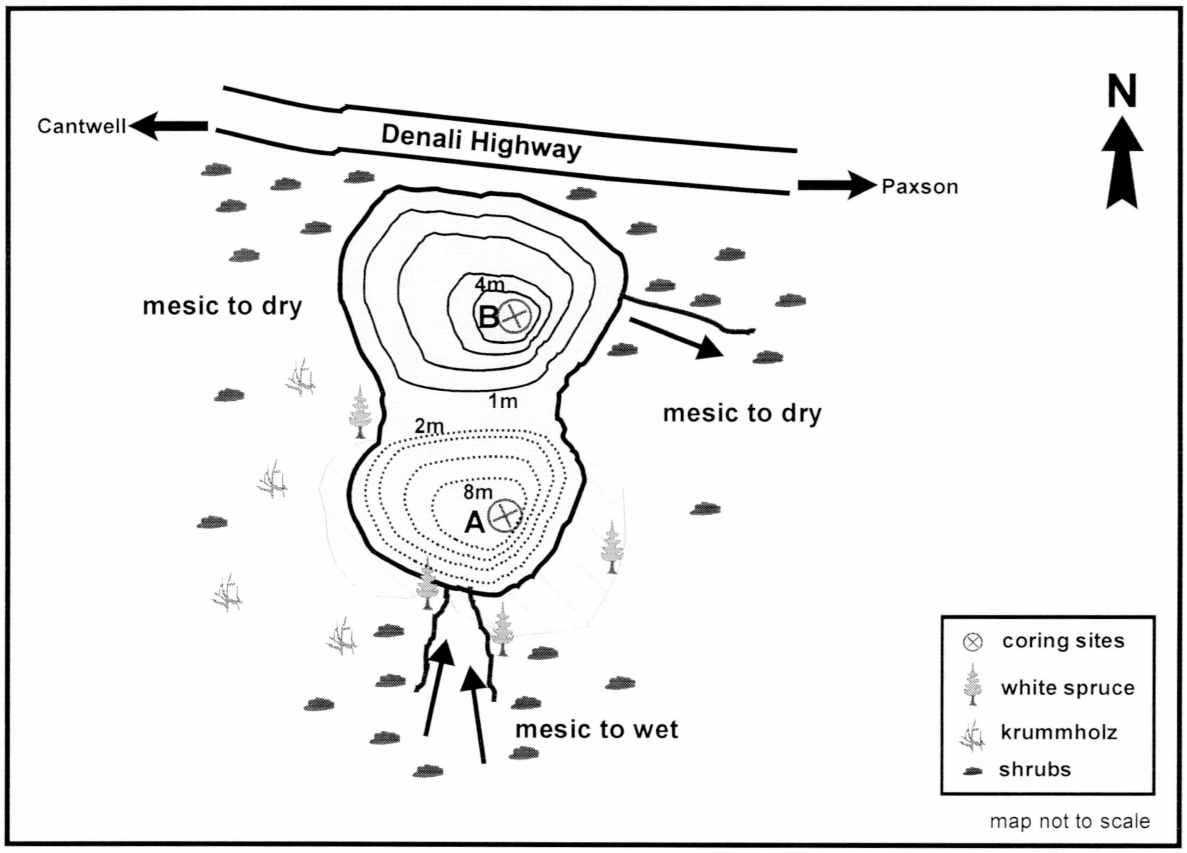

Fig. 12: Nutella Lake bathymetry, coring sites and landscape description.

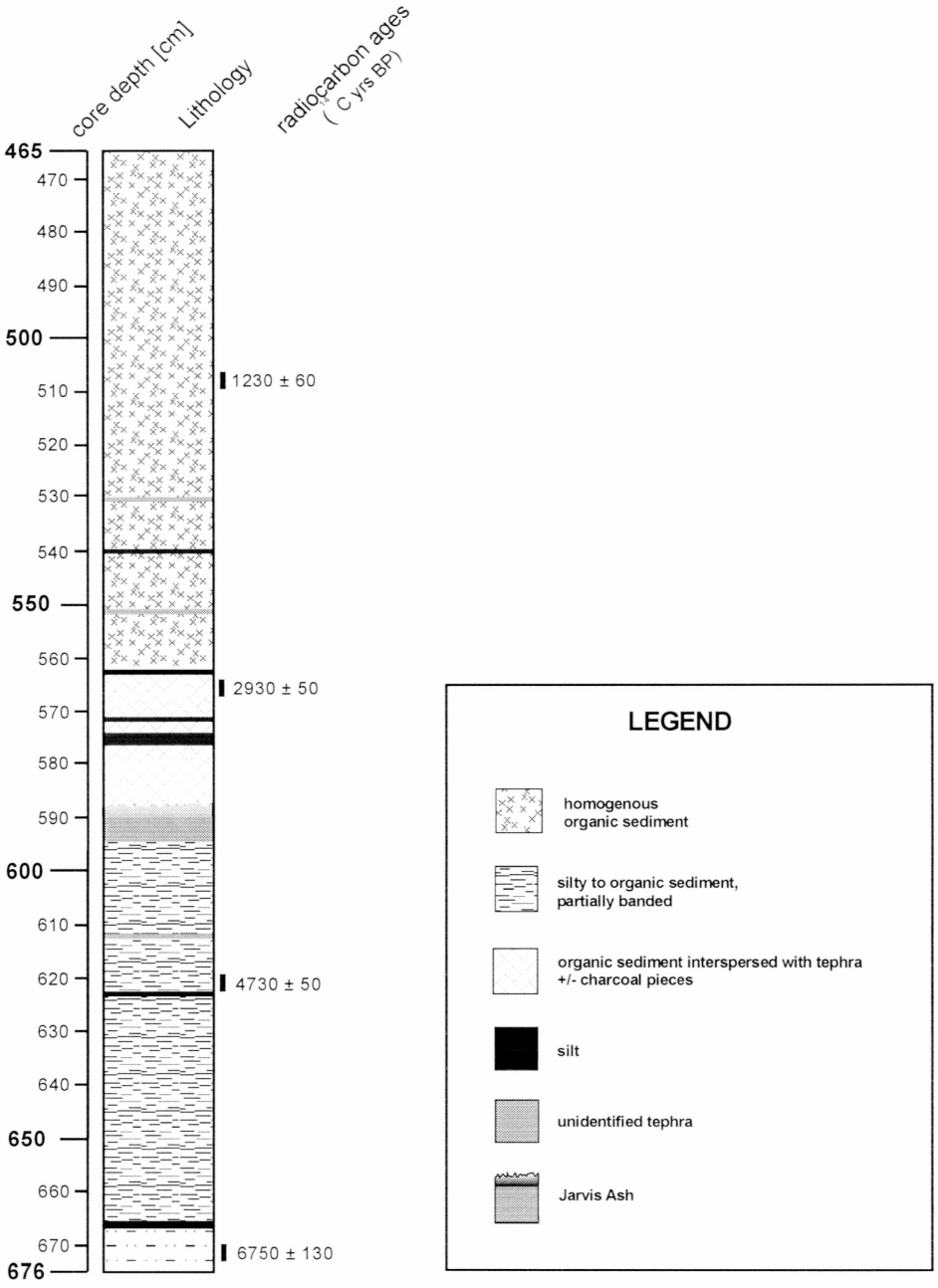

Fig. 13: Lithology and radiocarbon dates from Nutella Lake.

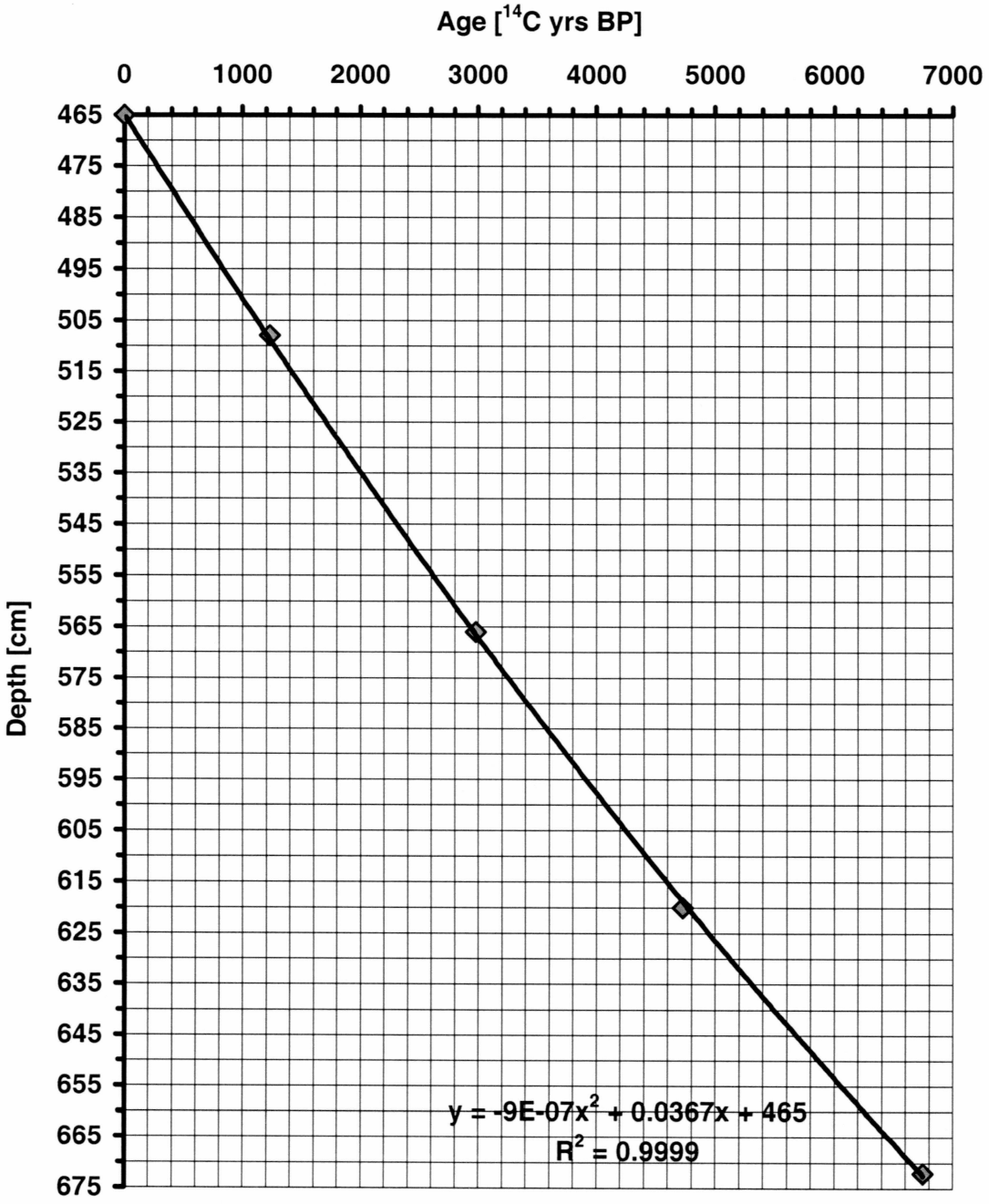

Fig. 14: Nutella Lake age-depth chronology.

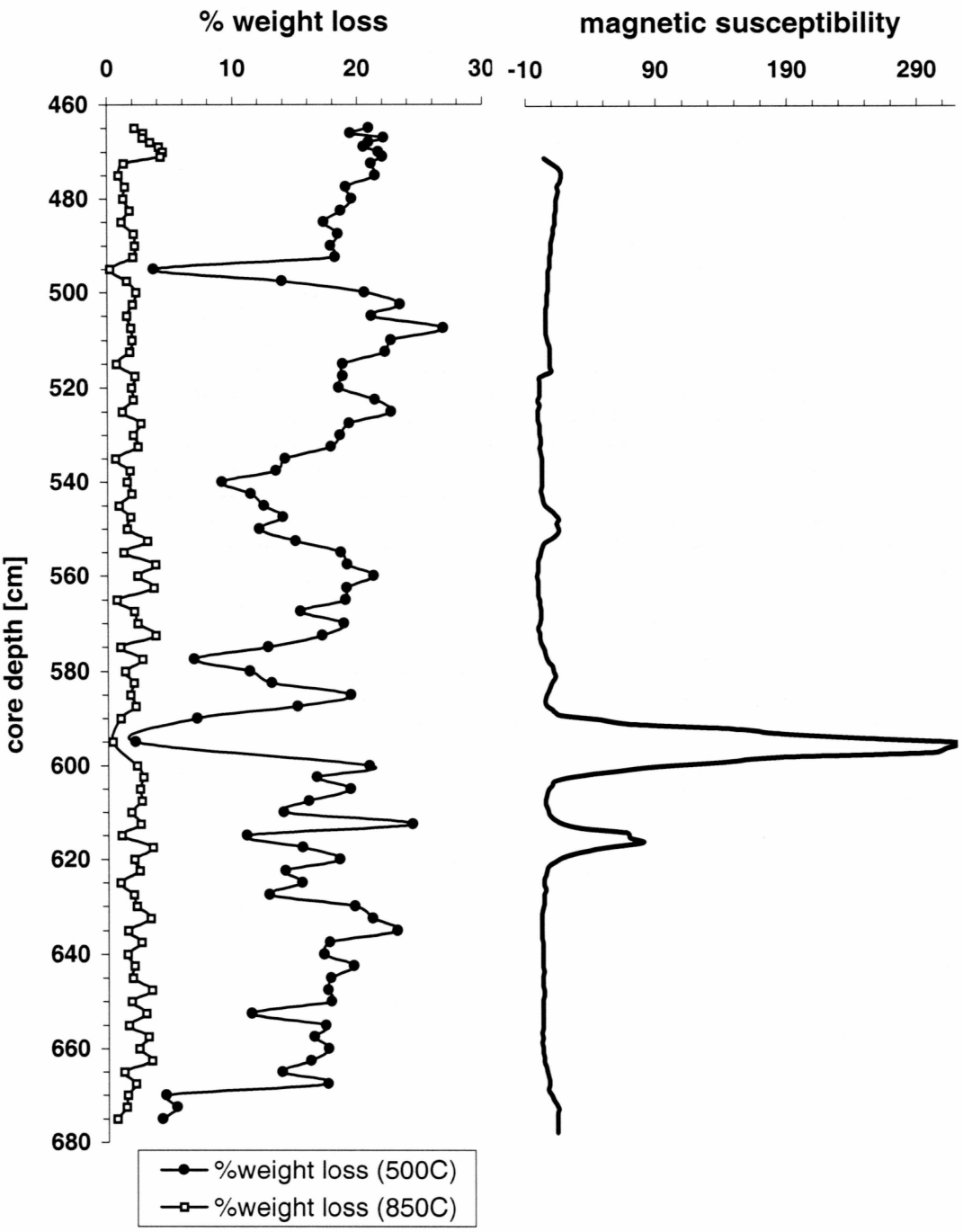

Fig. 15: LOI and magnetic susceptibility measurements from Nutella Lake.

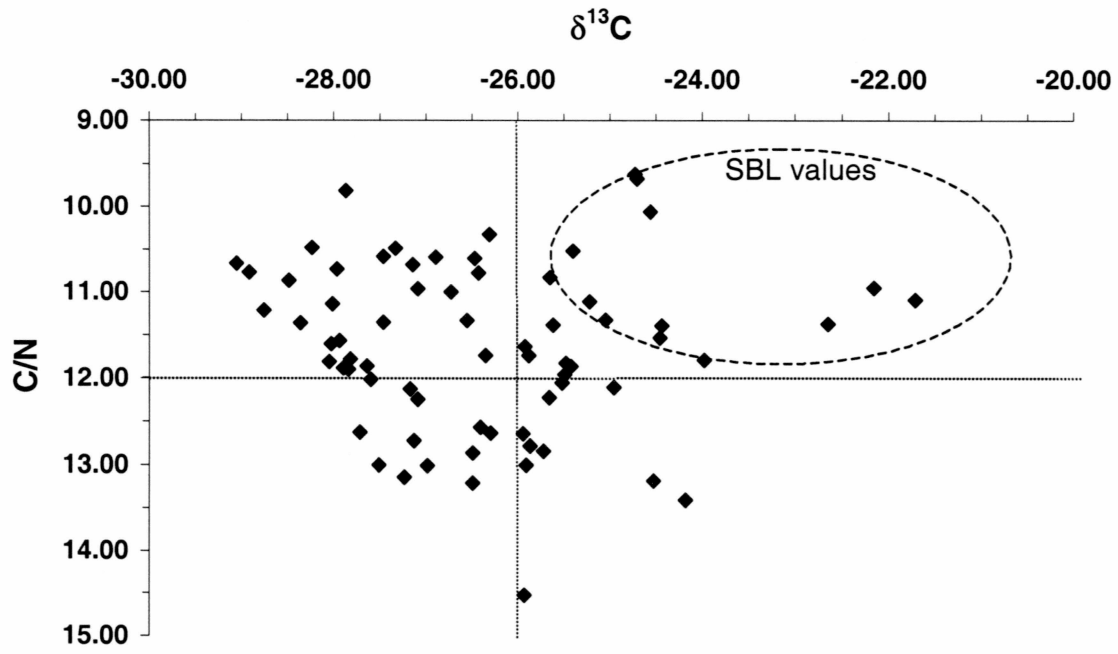

Fig. 16a: Correlation between $\delta^{13}C$ and C/N from Nutella Lake.

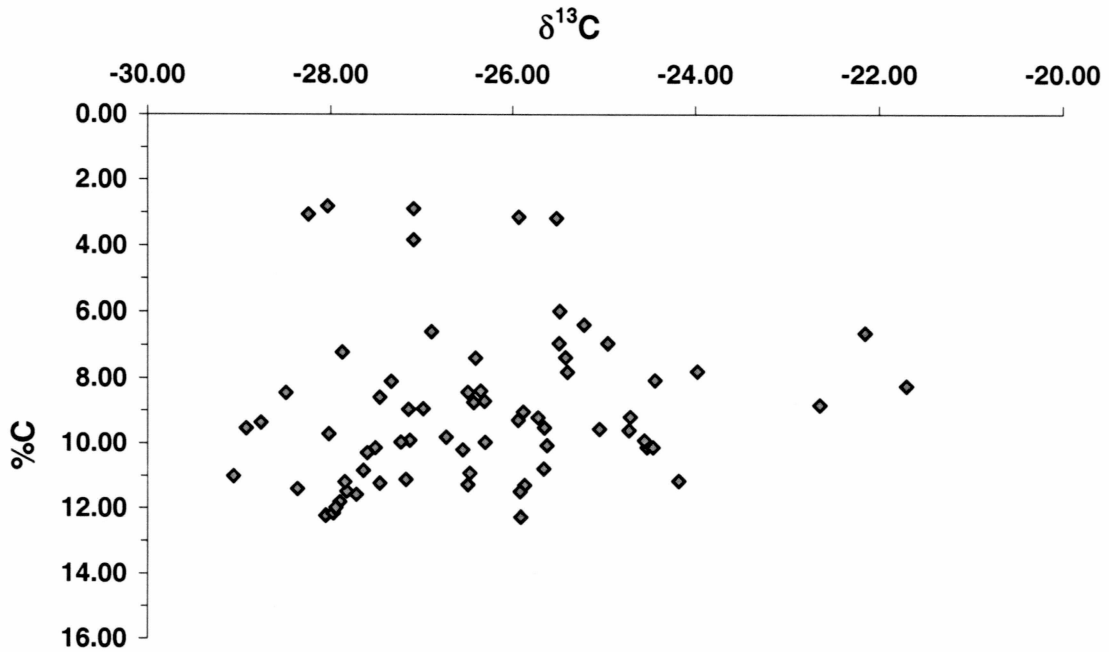

Fig. 16b: Correlation between $\delta^{13}C$ and %C from Nutella Lake.

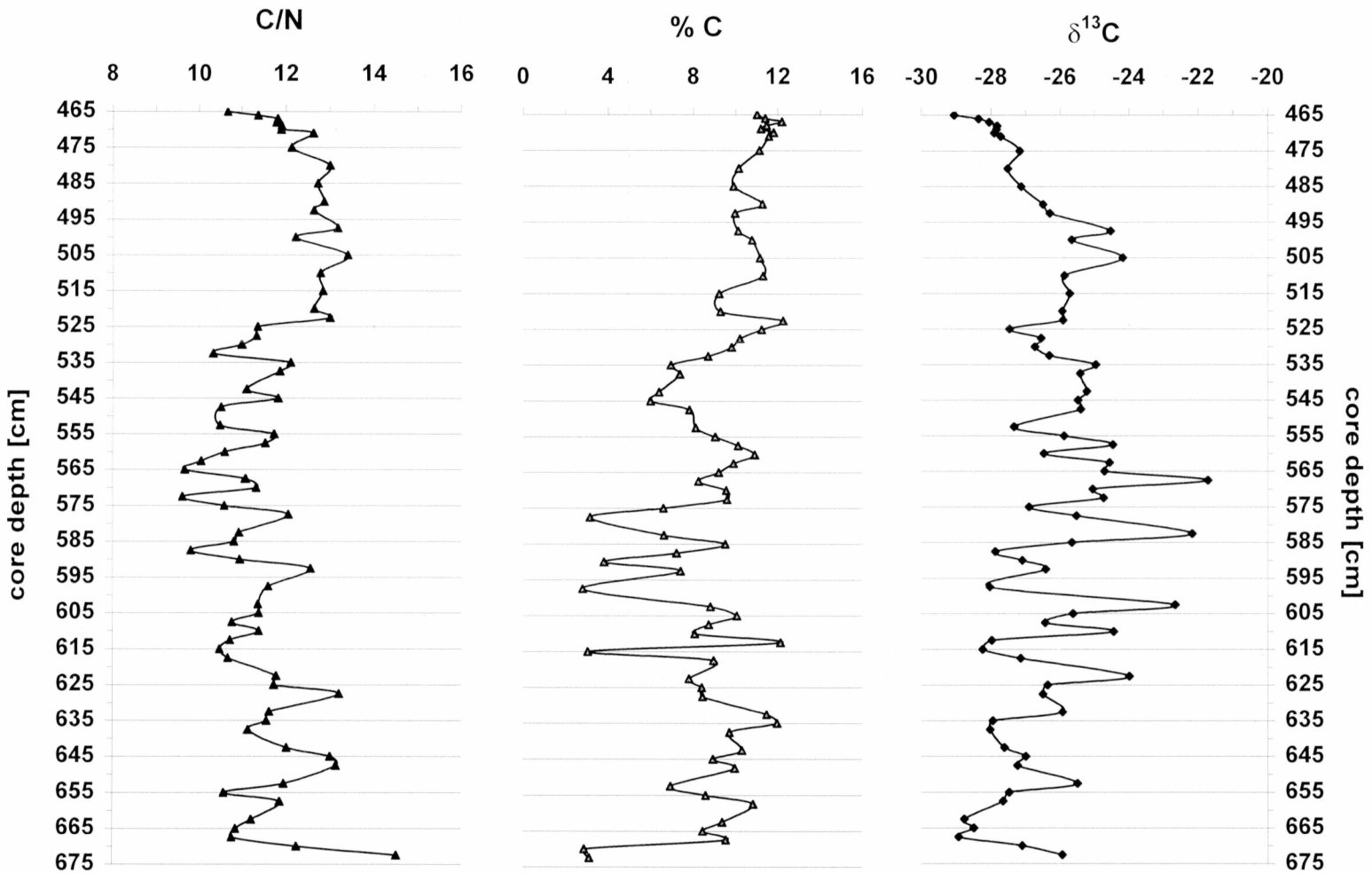

Fig. 17: A detailed diagram of carbon stable isotope data Nutella Lake.

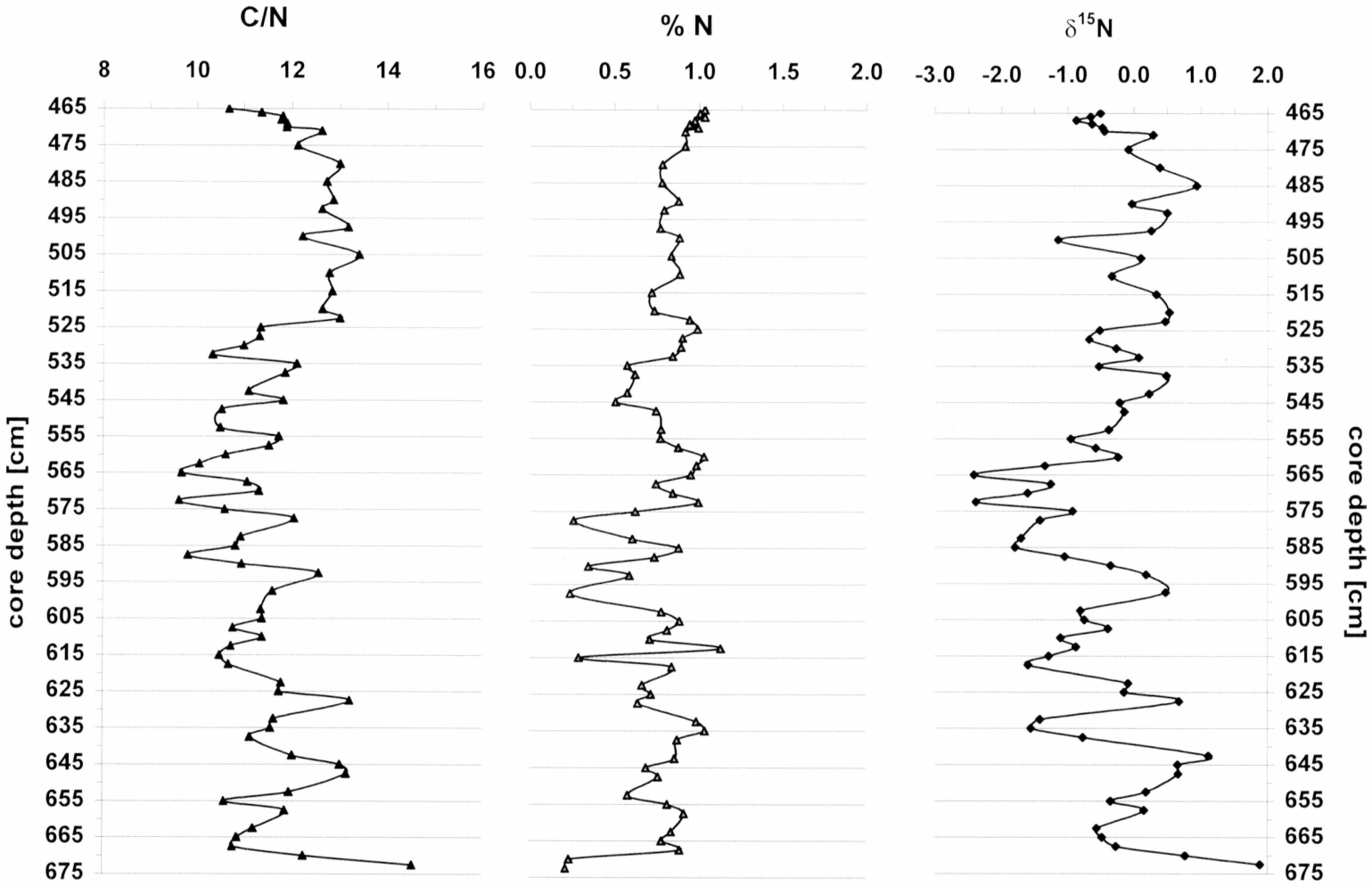

Fig. 18: A detailed diagram of nitrogen stable isotope data Nutella Lake.

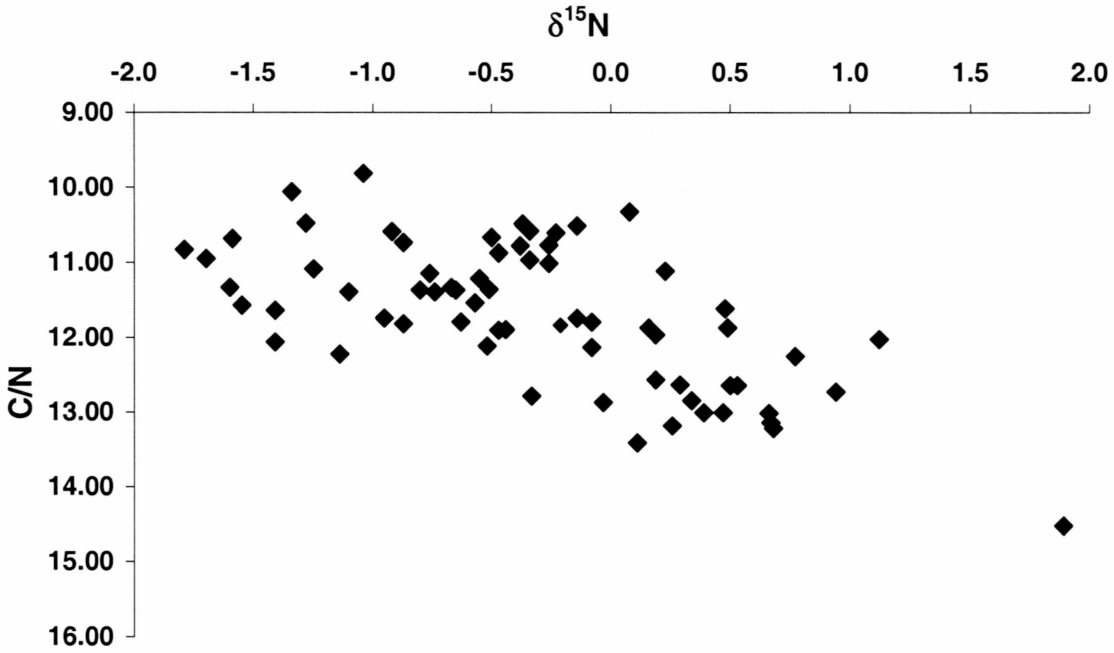

Fig. 19a: Correlation between $\delta^{15}N$ and C/N ratios from Nutella Lake.

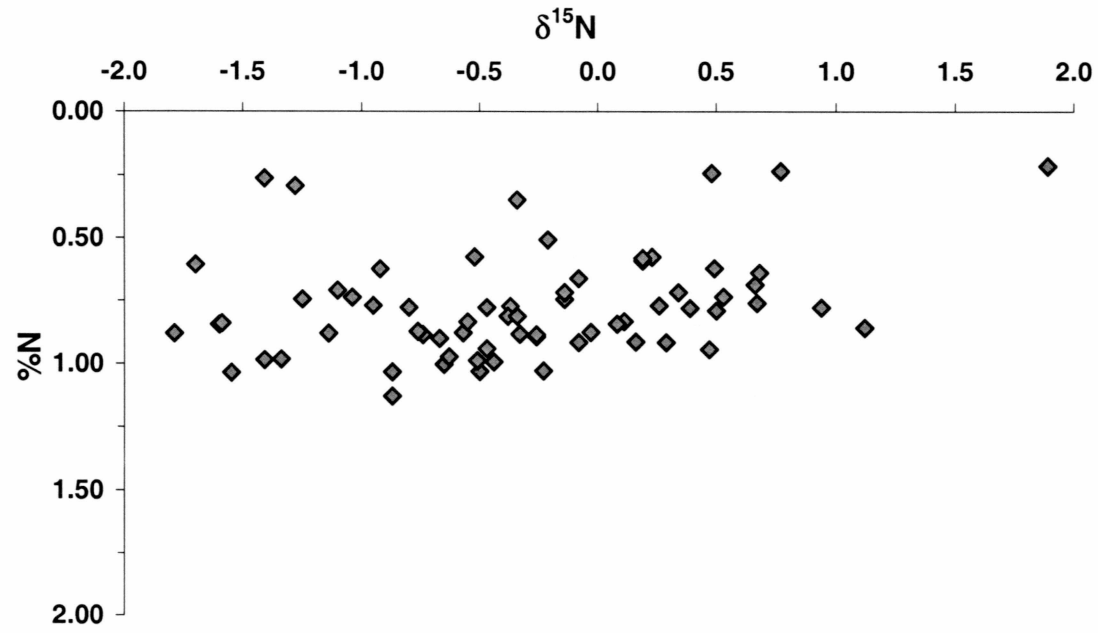

Fig. 19b: The relationship between $\delta^{15}N$ and the nitrogen content of Nutella Lake.

Fig. 20: Nutella Lake pollen percentages.

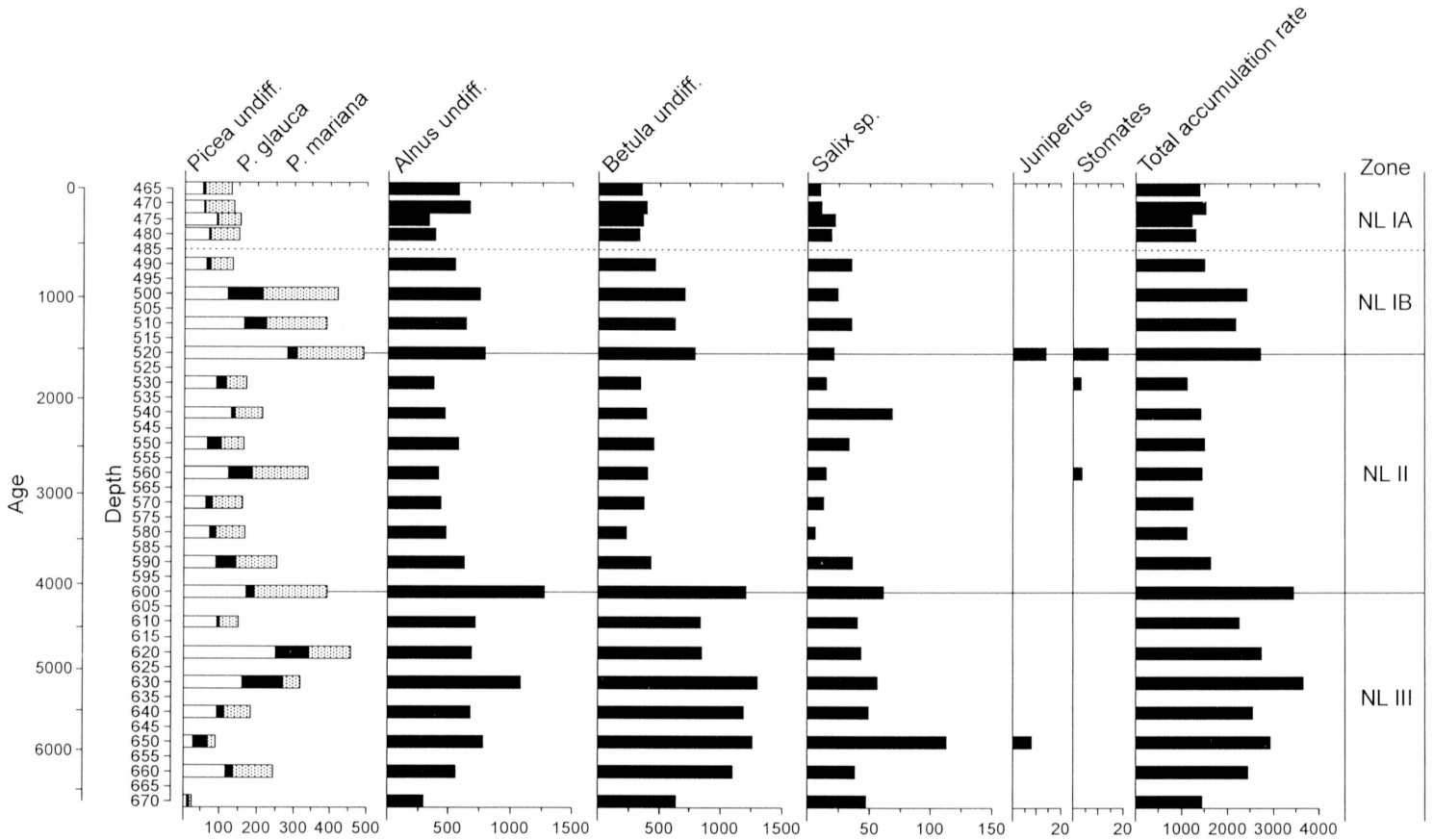

Fig. 21a: Nutella Lake pollen influx diagram (trees and shrubs).

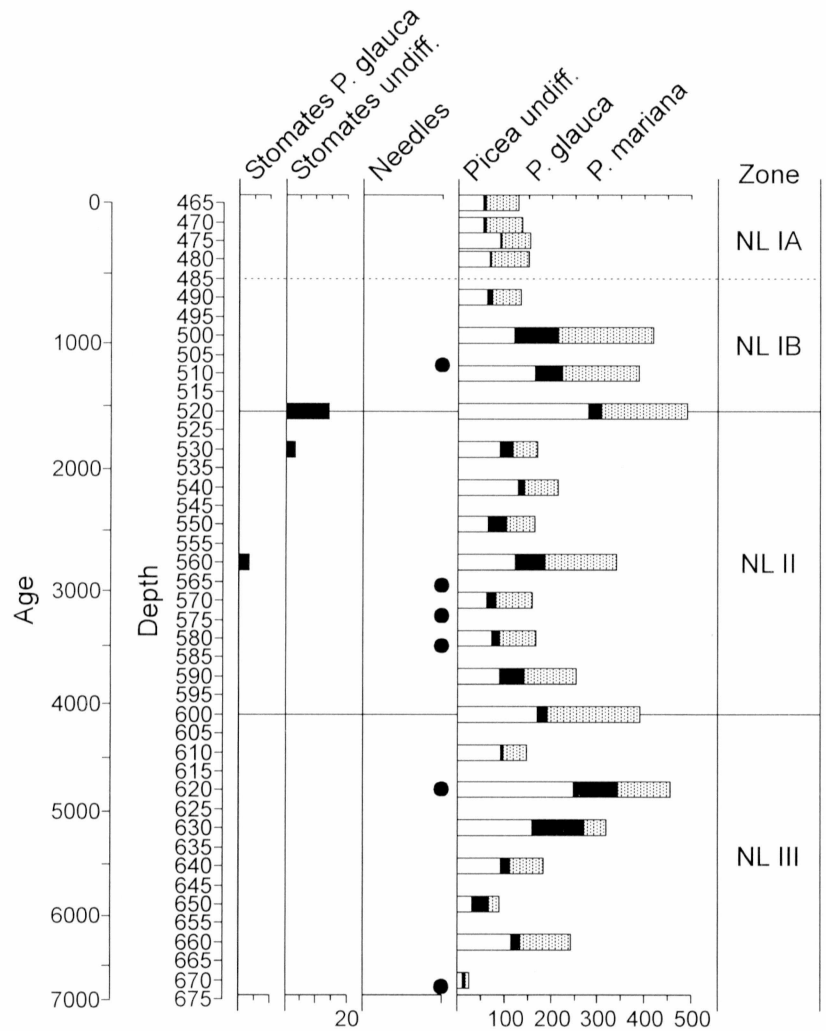

Fig. 21b: Nutella Lake spruce pollen and macrofossil diagram.

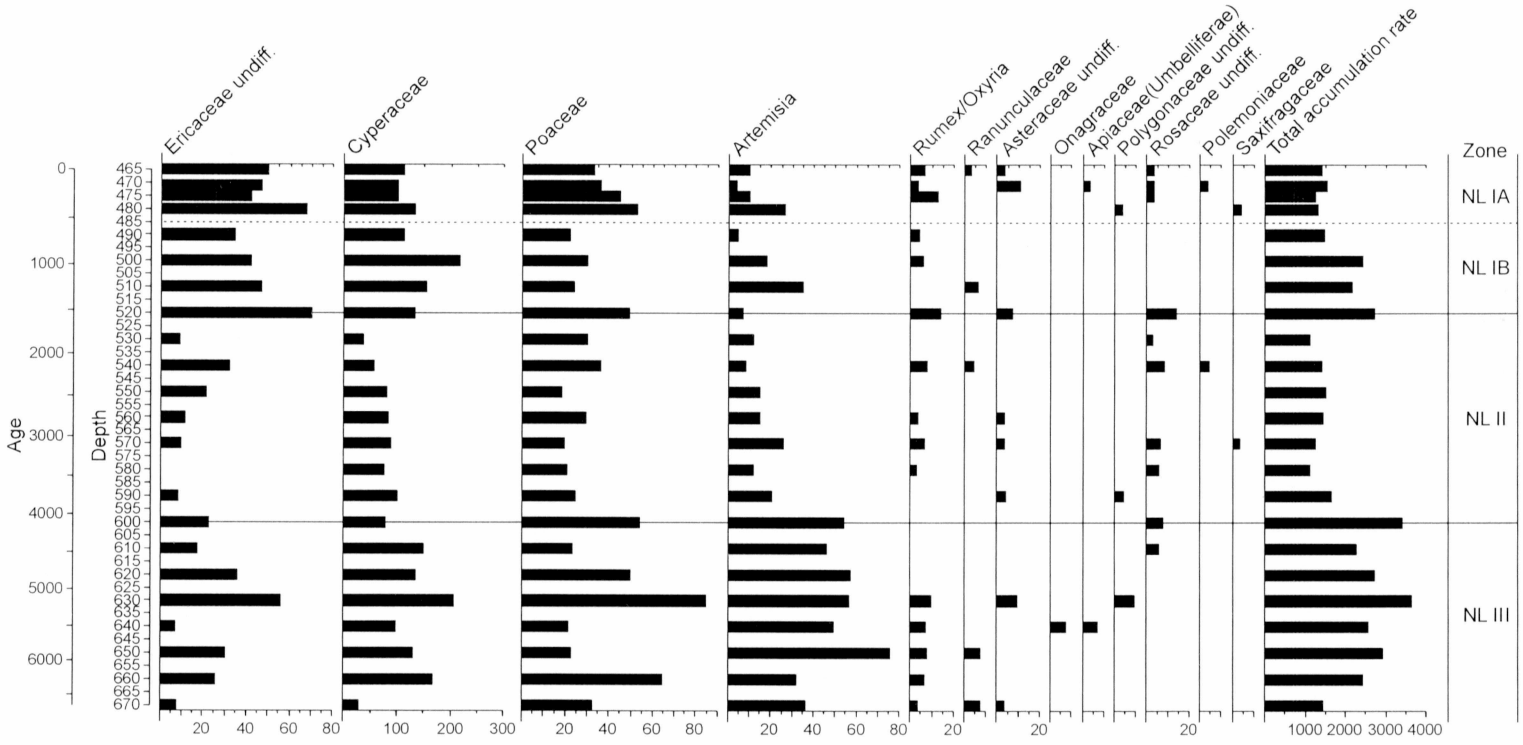

Fig. 21c: Nutella Lake pollen influx diagram (herbs).

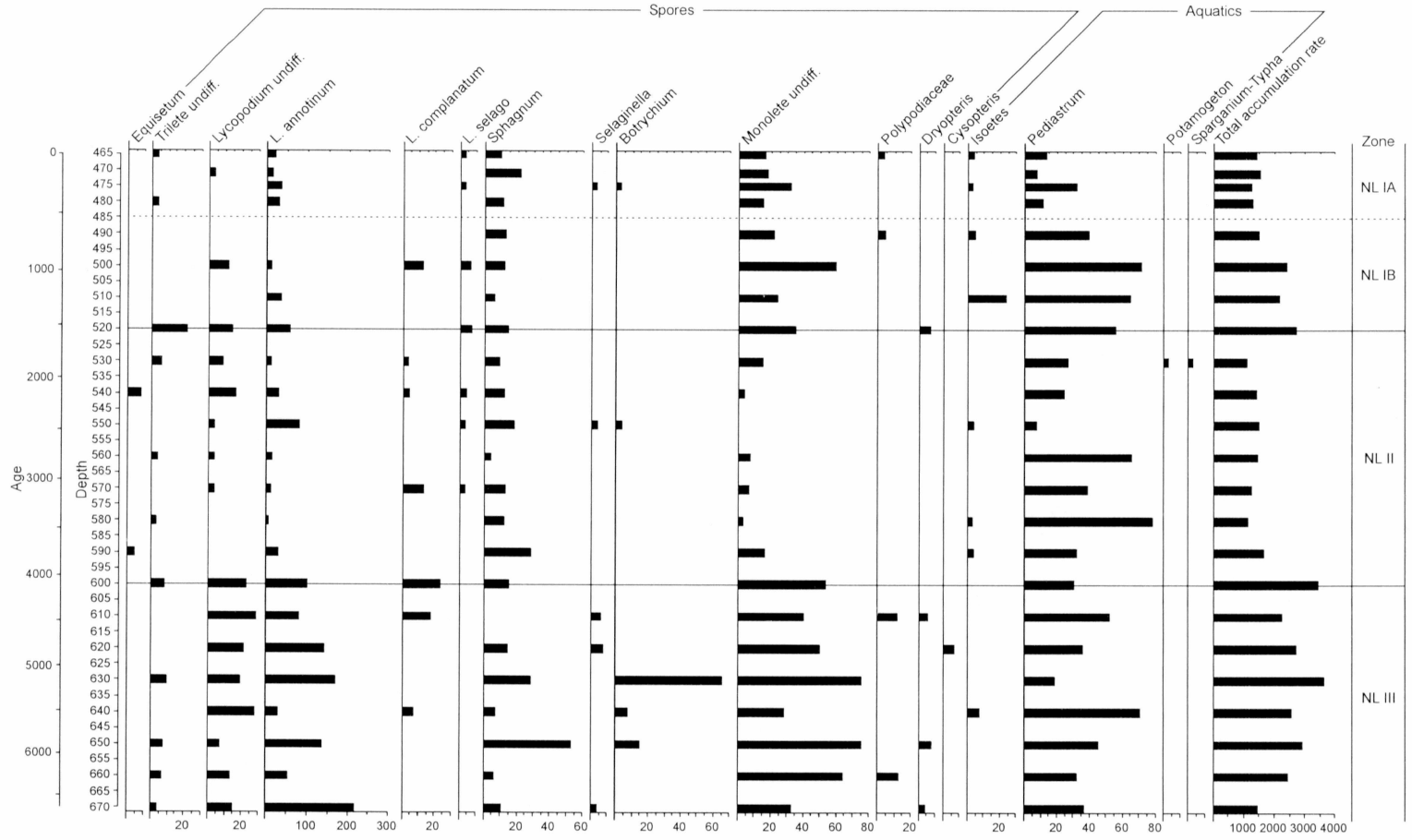

Fig. 21d: Nutella Lake pollen influx diagram (spores and aquatics).

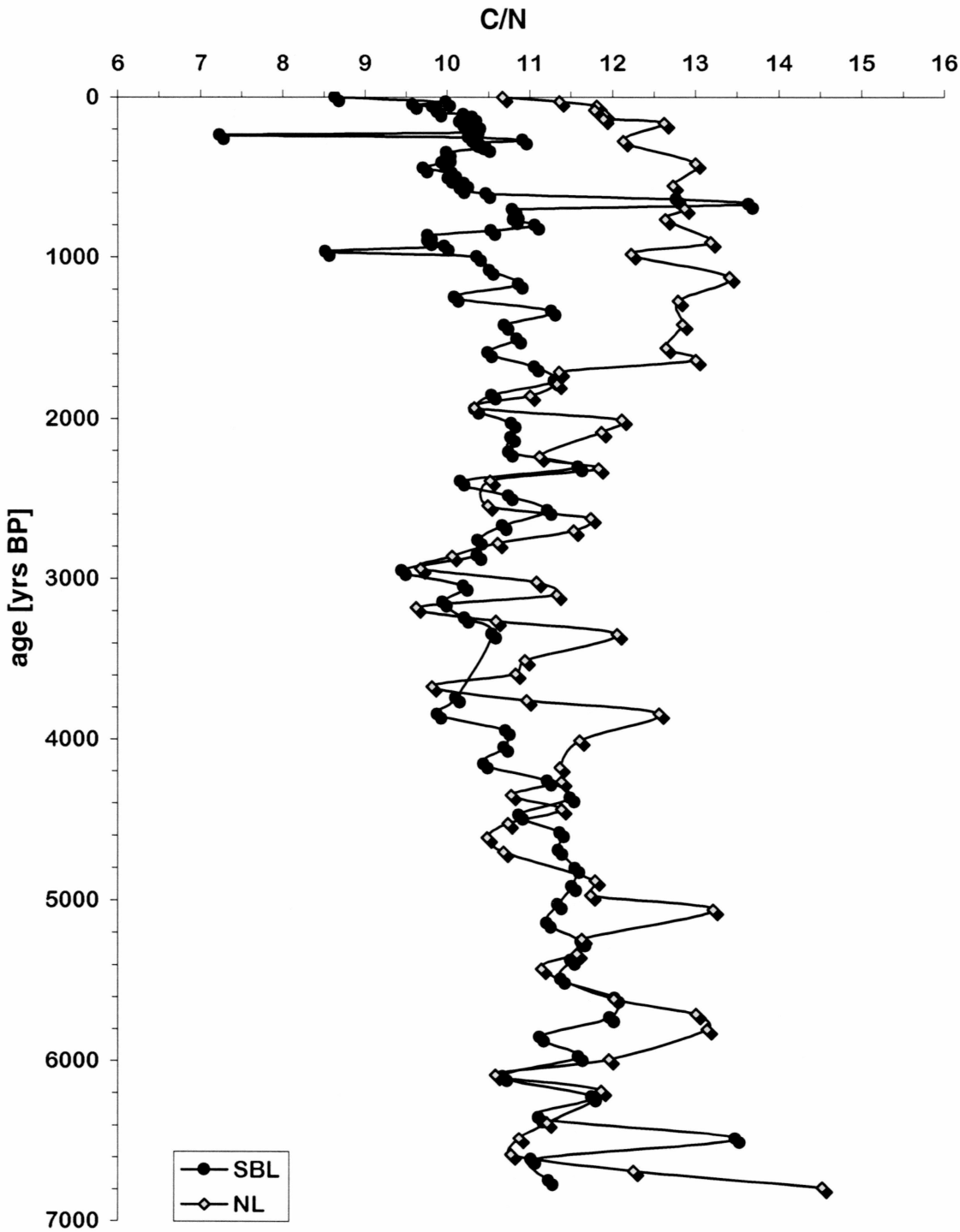

Fig. : 22a: A comparison of C/N ratios from Swampbuggy and Nutella Lake.

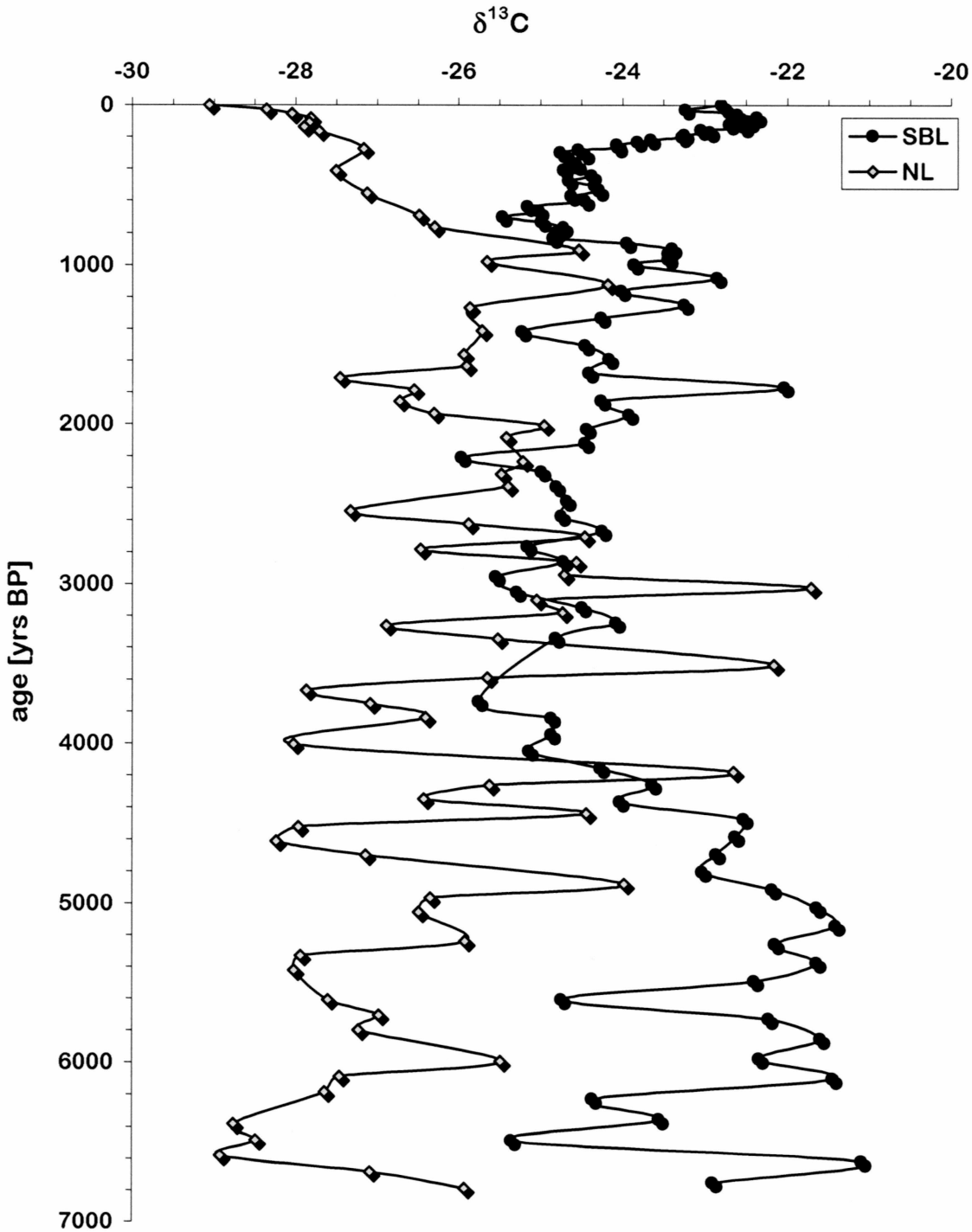

Fig. 22b: A comparison of $\delta^{13}C$ values from Swampbuggy and Nutella Lake.

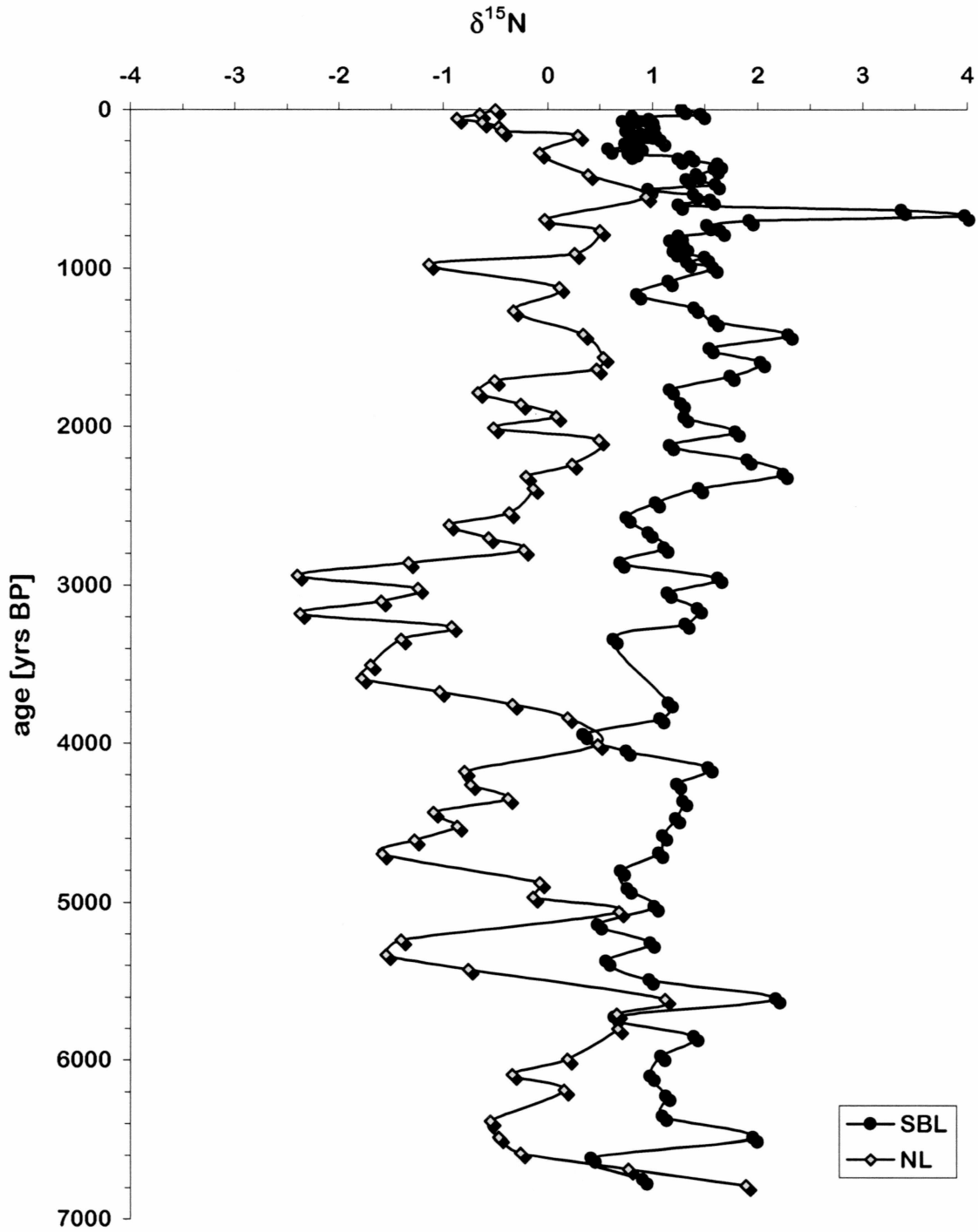

Fig. 22c: A comparison of $\delta^{15}N$ values from Swampbuggy and Nutella Lake.

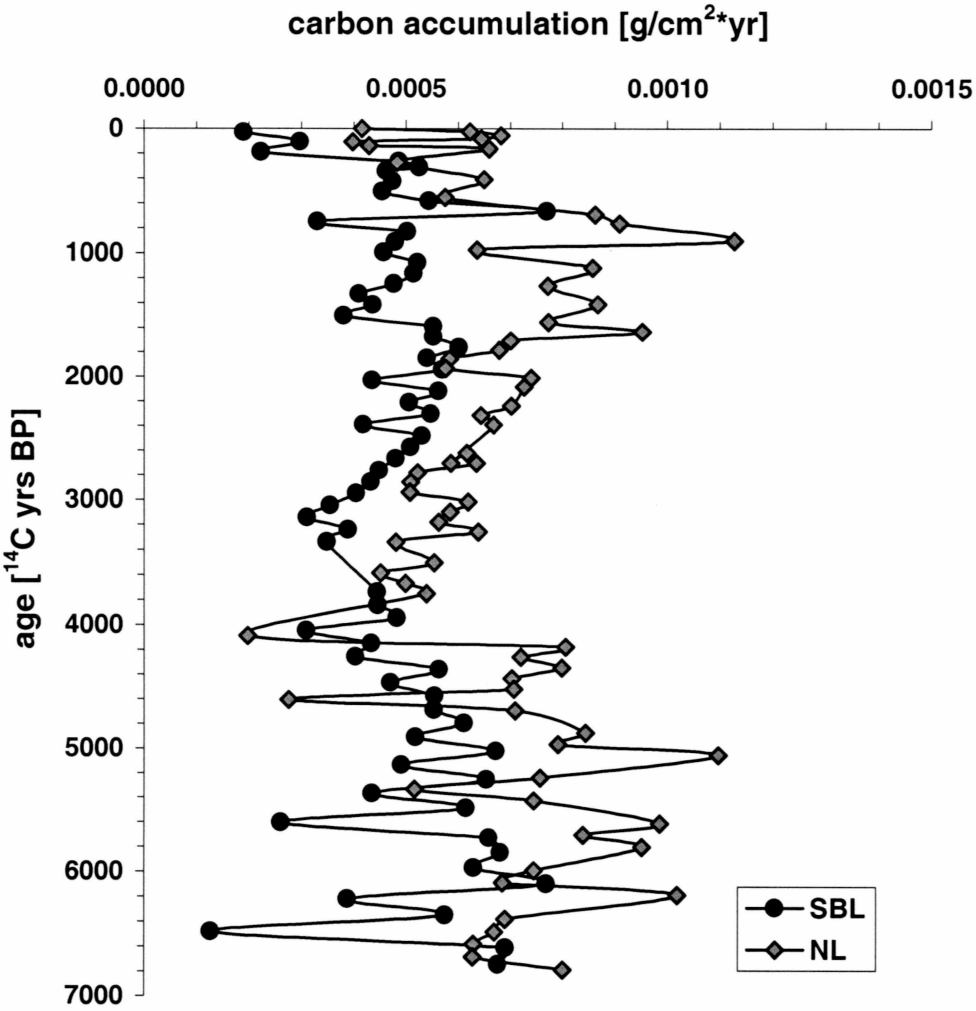

Fig. 23: Carbon accumulation rates from Swampbuggy and Nutella Lake.

APPENDIX A: INTERPRETING STABLE ISOTOPES FROM LACUSTRINE SEDIMENTS

Lakes sediments present a vast source of paleoenvironmental information and although lake sediments present a dynamic system that undergoes a variety of biogeochemical processes after deposition, the sedimentary record is fairly inert to major post-depositional transformations and provides useful insights into the history of the lake. Sedimentary organic matter, in particular, can be used to indirectly reconstruct climate changes in the past as a function of aquatic productivity and ecosystem variations because the organic fraction of the sediment reflects the biological activity and the overall dynamics of the overlying water column. Stable isotope analysis has been widely applied in ecological and environmental sciences while its utilization as a proxy record for paleoclimatological changes is a fairly new approach that will be discussed on the following pages.

Stable isotopes in general. The measurement of stable isotopes from lake sediments may provide information not only about the source, but also about processes during the formation of the material of the organic matter.
Stable isotopes are expressed in ‰ (per mill) and are defined as:

$$\delta R = \frac{R_{sample} - R_{standard}}{R_{standard}} \times 10^3$$

$R = {}^{13}C/{}^{12}C$ and ${}^{15}N/{}^{14}N$ respectively
Stable isotopes are measured against an international standard. The PeeDee Belmnite (PDB) is used for carbon measurement while air is used as standard for nitrogen measurements because ^{15}N in the atmosphere can be assumed constant (Letolle, 1980).

Carbon Stable Isotopes. The isotopic signature of carbon is dependent on many, often interrelated, factors. Most important are :

a) the isotopic signature and relative concentration of the source carbon, such as the contributions of autochthonous versus allochthonous carbon

b) isotopic effects through biochemical processes

c) isotope effects during digenesis

(Deines, 1980)

A process that significantly affects the carbon isotope composition of lacustrine sediments is photosynthesis. Dissolved inorganic carbon (DIC) from the surface waters is removed by autotrophic organisms which is a process that generally results in an enrichment of the lighter isotope ^{12}C in the organisms while the source material, dissolved inorganic carbon (DIC), in the lake water becomes gradually enriched in ^{13}C (McKenzie, 1985.) Upon burial the isotopic signature of the organisms is imprinted in the sediment. Higher productivity in the lake often results in relatively high $\delta^{13}C$ values of the sediment organic matter. This is caused by increased removal of the lighter carbon isotope from the carbon pool during summer, hence enriching organisms in the heavier isotope. Thus, the relative amount of the source carbon plays an important role in determining isotopic fractionation. The degree of fractionation also depends on the initial isotopic signature of the carbon source. While terrestrial plants utilize a fairly constant source of carbon, e.g. atmospheric CO_2, the carbon source of aquatic communities is extremely variable (Deines, 1980) and its isotopic composition may represent a complex mixture of different carbon signatures. A lake's carbon pool is primarily fed by the diffusion of atmospheric CO_2 into the lake as well as influx from groundwater, streams and surface run-off. The $\delta^{13}C$ value for atmospheric CO_2 is relatively heavy while the influx of terrestrial material contributes much lighter values. Carbon will also be generated through respiration and the decay of older sedimentary organic matter. Low $\delta^{13}C$ values can be expected from a system that relies heavily on a "respired" carbon source (Finney, 1995). The relative contribution of each of these factors will ultimately determine the isotope signature of dissolved organic carbon (DIC) that will be used by photosynthesizing biota in the lake. The $\delta^{13}C$ for DIC generally exhibits intermediate value between 10-16‰ (Stuiver, 1975). The fractionation factor of biota in the lake differs significantly between groups of organisms. In the terrestrial environment, carbon pathways of the biota determine the amount carbon fractionation. Plants that utilize the C3 pathway are usually isotopically lighter than C4 plants. CAM plants are intermediate between those two (Deines, 1980). In lacustrine environments, the relative amount of planktonic versus submerged macrophytes will influence the final isotopic signature of

lacustrine organic matter. Increased macrophyte production will lead to an enrichment of $\delta^{13}C$ values in sediment organic matter (Stuiver, 1975).

Table A1: Table summarizing the $\delta^{13}C$ values of major components in a freshwater ecosystem.

	sample type	$\delta^{13}C$ (‰) range	$\delta^{13}C$ (‰) average
ATMOSPHERIC	atmospheric CO_2	-7.8 to -12	-8
AQUATIC	plankton	-42 to > -18[2]	-30
	macrophytes	-30 to -12	-19
	shore vegetation	(no data available)	-27
TERRESTRIAL	C-3 plants	-25 to -30	-28
	C-4 plants	-8 to -12	-13
	CAM	-10 to -20	-15
LACUSTRINE	sediments	-8 to –30[1]	-26
	DIC	-15 to -6	-20
	$CaCO_3$	-15 to 0	(no data available)

(all data from Coleman & Fry, 1991 except [1] data from Stuiver, 1975 and [2] data from B. Finney, personal communication and Gu et al., 1996)

Many oxidative processes occur between photosynthesis and the incorporation of organic matter into the sediment. (Deines, 1980). Once organic matter is formed, it is constantly reworked and degraded by microorganism in the water column and in the sediment. (Meyers and Ishiwatari, 1991). Certain chemical groups, which differ significantly in their isotopic composition, may be eliminated through these degradation processes while others are more likely to preserve. As a consequence, the isotopic composition of the average organic matter may shift to a value that is extremely deviant from its original. In general, $\delta^{13}C$ values of sedimentary organic matter ranges from -8‰ to -32‰ (Stuiver, 1975). Table A1 summarizes the $\delta^{13}C$ values of major components in lakes. It is unclear from the literature whether major isotopic shifts occur during

digenesis. Deines (1980) argues that heavier carbon is removed from the sediment upon burial through decarboxylation reactions. Meyers & Ishiwatari (1985) found no severe diagenetic shifts in isotopic composition once the sediment is buried although they suggest that some information will be lost due to integration in the food web.

Nitrogen Stable Isotopes. Nitrogen isotopes from organic matter may provide similar information about lake paleoproductivity as do carbon isotopes. The isotopic signature of bulk organic matter reflects the source and sink of nitrogen compounds in the lake and processes these compounds have undergone. The $\delta^{15}N$ ratio of naturally occurring substances varies greatly within a range of -6 to +21‰ (Wada, 1975). The use of nitrogen isotope is much less common than the use of its carbon counterpart, which may be due to the complexity of the nitrogen cycle in lakes and the small fractionation factor of nitrogen (Handley and Raven, 1992). Nitrogen passes through many forms and oxidation states and only a restricted group of microorganisms mediates the reactions in the cycle (Collister and Hayes, 1991). The most common forms of nitrogen in lakes are nitrate (NO_3^-) ammonium (NH_4^+) and organic nitrogen (org-N). In an idealized lake organic matter produced in the water column will sink and is subject to nitrogen mineralization during decomposition to produce ammonium and CO_2. In highly alkaline and saline lakes where mineralization rates are high ammonia may lost due to ammonia volatilization. In anaerobic environments ammonium is usually directly assimilated by plants and bacteria while in aerobic environments, it is oxidized by nitrifying bacteria to nitrate. Nitrate is further reduced to elemental nitrogen (N_2) during denitrification in oxygen-reduced waters or is assimilated by lake organisms. The processes of denitrification and associated loss of N_2 from the lake is counterbalanced by nitrogen-fixing bacteria that convert elemental nitrogen to org-N (Collister and Hayes, 1991). $\delta^{15}N$ in lake organic matter depends on the extent to which nitrogen is recycled in the lake. Recycling of organic matter or high contributions of ^{15}N-enriched material to the lake's nitrogen pool may result in organic matter that is highly enriched in ^{15}N (Collister and Hayes, 1991).

Organisms generally discriminate against the heavier nitrogen isotope although the degree of fractionation varies from species to species. Isotopic fraction during nitrogen assimilation depends on the organism itself in the lake and the form of nitrogen that is assimilated by the organism. The fractionation factor during nitrogen fixation is

close to 1.000 (Handley and Raven, 1982). Thus, nitrogen-fixers, such as cyanobacteria, obtain $\delta^{15}N$ values close to 0‰. Non-fixing phytoplankton exhibits a wider range of isotope ratios are commonly heavier than N_2 fixing organisms (Gu et al., 1996). The degree of fraction is also dependent on the size of the nitrogen pool and nutrient supply. When a lake is N-limited, fractionation may be small while a large pool may result in greater fractionation relative to its use.

APPENDIX B: TREE-RING DATA

Tree cores were collected in summer 1997 around the vicinity of both Swampbuggy and Nutella Lake. While this project was only intended as an experimental undertaking, the results provide an important insight into the age structure of spruce trees around the study sites. I collected a total of 39 tree cores from white spruce in a north-south and east-west transect around Swampbuggy Lake and a total of 10 tree cores from selected sites, mostly small drainages and depressions, south of Nutella Lake. The cores were collected as close to the ground as possible using an increment tree borer. Only cores with entire piths were considered for further analysis. The diameter at breast height (DBH) and coring height (CH) was measured for all trees unless otherwise noted. In addition, stand and tree-specific characteristics were recorded. Data are shown in Table B1 and Table B2, respectively. Tree ages are only approximate as they have not been corrected for coring height.

Swampbuggy Lake trees can be divided into two groups: the "hillside tree" group comprises trees that grow along the steep mountain side to the north of the lake (groves A-L) while "lakeshore trees" include trees along the west and north shores of Swampbuggy Lake (grove LC). The mean and average age values of lakeshore trees are slightly higher than those of the hillside trees (Fig. B1). Open forest-tundra currently dominates the east side of the lake, but new recruitment, and increasing density of the forest-tundra, is evident in this area which confirms the subtle trend in the numerical data that recruitment has been occurring during the 20th century. Tree growth may have been strongly dependent on site-specific factors, rather than regional climate. At Nutella Lake, krummholz is a common growth form of spruce whereas tall standing trees are sparse. Tree growth, in general, is limited to moister drainage channels and gullies and sheltered areas. Upright trees often have multiple stems, which derived from one or more layering branches. Ring counts of Nutella Lake trees range between 60 and 140+ years but there is no correlation between the DBH and the ages of the trees (Fig. B2). Increased recruitment of saplings has been observed in the vicinity of the lake. Whorl counting of young trees showed an age of approximately 15-40 years, with an average of 25.

Table B1: Tree-ring data from Swampbuggy Lake.

ID#	DBH [cm]	CH [cm]	RING COUNT (average yrs)
A1	20.8	38.5	55
A2	28.3	45.0	66
A3	22.4	38.3	54
B1	19.1	45.5	62
B2	19.9	45.0	58
C1	17.3	36.5	37
C2	27.8	43.0	64.5
C3	28.0	32.0	60
D1a	38.4	43.0	55
D1b	38.4	18.0	59.5
E1	22.4	31.0	*nc*[1]
F1	30.1	31.0	74.5
F2	31.0	52.5	82
F3	31.5	45.0	69
G1a	38.8	32.0	77
G1b	38.8	27.5	*nc*[1]
H1	50.7	40.2	55
H2	25.9	25.9	91.5
I1	34.5	45.5	66
I2	27.1	26.0	*nc*[1]
J1	31.0	24.0	135
J2	19.4	34.0	*nc*[1]
K1	16.8	56.5	67.5
K2	16.2	25.0	67
L1	22.2	45.5	*nc*[1]
L2	21.8	40.0	*nc*[1]
LC1	34.6	43.0	99
LC2a	15.0	23.0	54
LC2b	*n/a*[2]	20.5	61
LC3	19.5	50.0	65
LC4	23.5	55.0	81
LC5	20.5	38.0	64
LC6	20.2	43.5	98
LC7	26.1	29.0	62
LC8	27.4	34.0	79
LC9a	*n/a*[2]	12.0	130
LC9b	52.0	45.0	114
LC10	46.4	54.5	139
LC11	26.2	27.0	67

nc[1]= tree rings could not be counted or counts were unreliable because tree core was missing the pith, or appeared to be rotten
n/a[2]= DBH could not be measured

Table B2: Tree-ring data from Nutella Lake.

ID#	DBH [cm]	CH [cm]	RING COUNT (average yrs)
TG1	22.5	62.0	124
TG2	17.0	30.5	139
WS1	16.7	45.0	57
WS2	23.3	26.0	86
VTT1	22.7	50.5	93
VTT2	19.5	25.0	90
VTT3	13.1	37.5	93
VTT4	17.2	35-40	91
FS1	11.7	59.0	107
FS2	15.6	79.5	122

The results from these tree ring data sets demonstrates that trees have been growing around the study sites for at least a century. Tree recruitment has increased during the past two or three decades. Nutella Lake trees possibly experienced a period of more favorable climate for growth during the past century as trees change from a layered to upright growth structure.

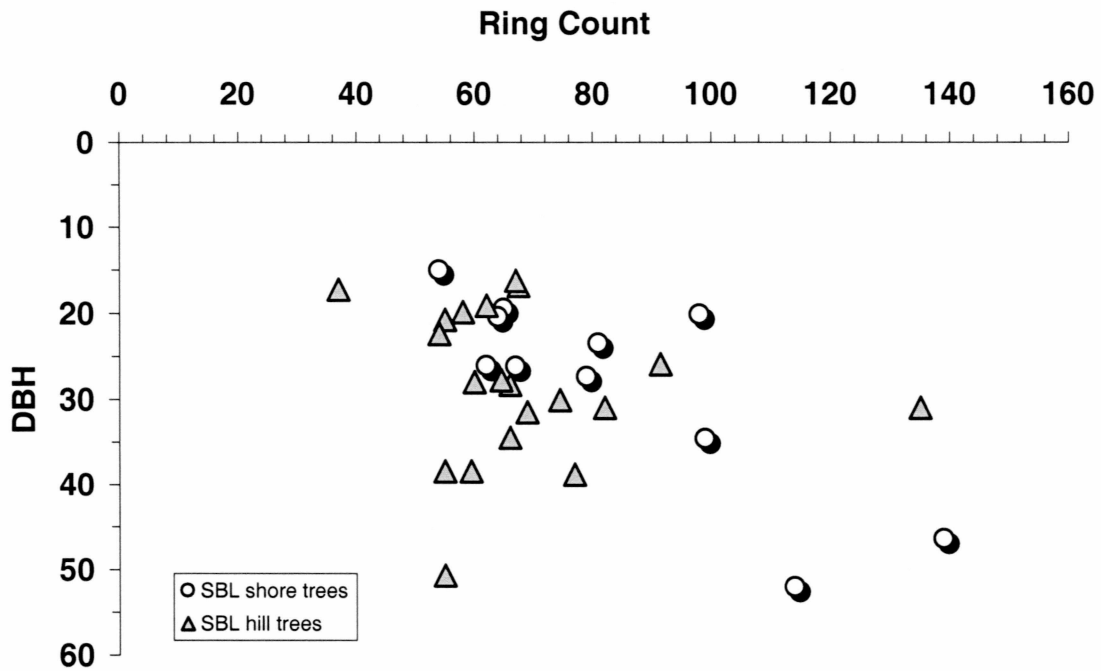

Fig. B1: Age structure of *P. glauca* from Swampbuggy Lake.

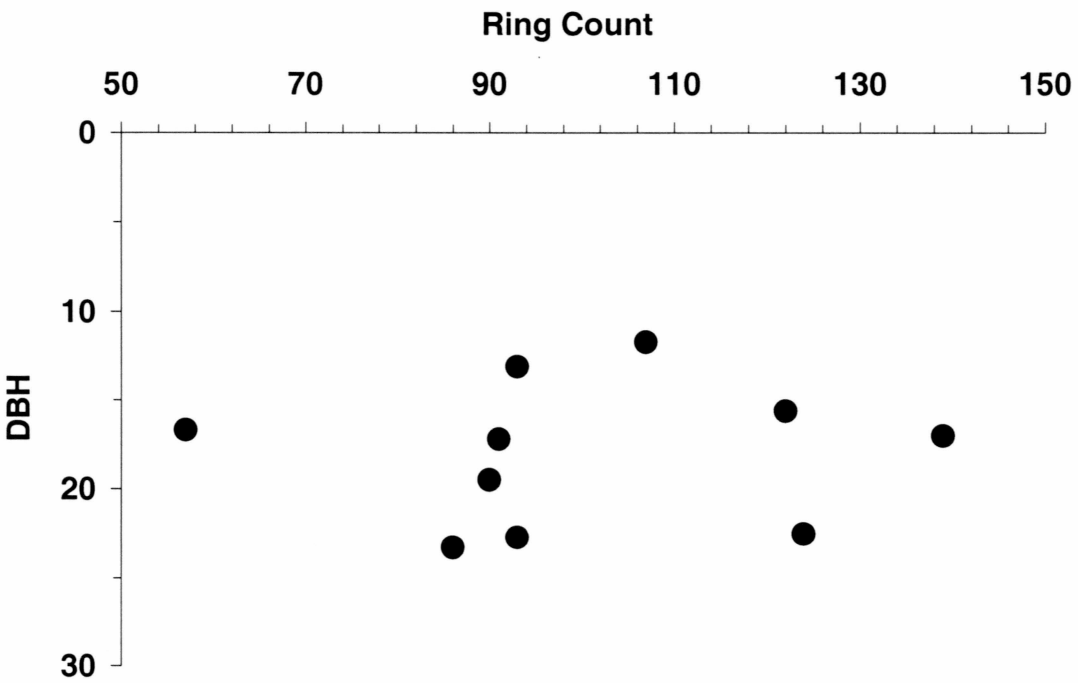

Fig. B2: Age structure of *P. glauca* from Nutella Lake.

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